

# DYNAMIC STIMULI AND SELF-REGULATION

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Yu Hao

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# DYNAMIC STIMULI AND SELF-REGULATION

Yu Hao, Ph.D.

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Human and environment influence each other dynamically and are co-adapting. Not only a specific stimulus influences people, but stimuli change may also trigger state transition. This dissertation treats dynamic stimuli with changing valence or intensity as probes to detect emotional responses and self-regulation, measuring electroencephalograph (EEG) and psychophysiological signals (ECG, skin conductance, eye tracking, respiration, etc.). I hypothesize that dynamic stimuli are more salient than static stimuli for emotional processes because they are unpredictable and consume more control resources. For example, intermittent noise may have a more negative impact than static noise. I designed four studies with different dynamic stimuli to understand how they influence emotion and the role of self-regulation.

Study 1 shows that the deterioration of attention inhibition after dynamic emotional processing may reflect the additional cognitive effort required to process dynamic shifts in affective stimuli. I also found evidence this relationship is exacerbated by chronic stress. Study 2 further examined how flexible self-regulation is related to flexible neural activity change during affective stimuli transitions. Study 3 examined cortical and cardiovascular regulation to neural responses in an ambient sound environment. This study implicated that environmental context can trigger different self-regulation mechanisms both cortically and in the autonomic nervous system. Study 4 examined the effect of dynamic changes in brightness on acute stress recovery. Contrary to study 1,

though dynamic sunlight captured more of people's attention than static sunlight, it reduced beta power, which was associated with more relaxation. These studies suggest dynamic stimuli with transitions have more impact on people, and this may happen via shifts in executive functioning (task-switching, inhibition, and working memory). Furthermore, the impacts of self-regulation vary according to context.

## BIOGRAPHICAL SKETCH

Yu (Hannah) Hao was born in Taiyuan, Shanxi, China and had lived there until finishing the undergraduate study at Taiyuan University of Science and Technology in Spring 2012. Then she came to the US to continue pursuing an education in Industrial Design for a master's degree at the Georgia Institute of Technology.

Since then, Hannah started to develop interests in neural mechanisms underlying human behaviors and how emotion is generated, transformed, and regulated during the interaction with the external environment. She was interested in utilizing technology and computational tools in studying human behaviors; therefore, she did an MS degree in Computational Science and Engineering. In Fall 2015, she began her Ph.D. study in the Department of Design and Environmental Analysis, supervised by Dr. Gary W. Evans, at Cornell University. While at Cornell, she designed experiments to examine neural signals, dynamic stimuli, and self-regulation. Apart from her major, she also did two minors: Cognitive Development and Applied Statistics.

After completing her Ph.D., Hannah will join the Center for Neuroscience and Society at the University of Pennsylvania as a post-doctoral researcher. With multidisciplinary experience, Hannah hopes to be a faculty member studying computational and cognitive aspects of human emotion and behavior, as well as artificial intelligence in developing mental health interventions for both clinical populations (e.g., anxiety disorders, major depression) and the general population (with more common challenges like stress).

To my mom

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Chapter 3 is a paper under review with co-authors Yao, L. and Evans, G. W.

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# CHAPTER 1

## INTRODUCTION

### 1.1 Motivation

Knowing one's emotional condition and knowing how to manage it are interrelated yet independent issues. People do not pursue conscious regulatory goals unless they have the motivation and ability to do so. But for a person who has already been suffering from mood disorder for a long period of time, it is hard for them to realize their current state or to manage to regulate their emotions. Thus, it is essential for the proposed regulatory model to not only design an interface that can clearly show mental states in real-time, but also motivates behavioral changes and influence emotional transitions.

Human behavior and the environment interact dynamically. Moreover, human cognitive and emotional processes as well as the external environment are dynamic systems. To simplify and model these dynamic, interactive systems, Figure 1.1 depicts a conceptual model of the relationship between humans and their environment. This figure also abstracts the two subsystems as engines having input and output attributes. In the double dynamic system, the current interaction output from one system becomes the next, subsequent input to the other system. In both human and environmental subsystems, there are inner mechanisms that generate output based on input. Briefly explained, human input and output are important elements for controlling both environmental changes (output) and environmental input resulting from human output. Human input can include interpretations of environmental stimuli, perception, recognition, etc. Human output can include physiological responses and behav-

iors. These human outputs can be measured and transformed into inputs to the environment.

The way we interact with the environment contributes to who we are. If technology is able to capture the dynamics of the interplay between human emotional processing and the influence of dynamic stimuli, this would have the potential to affect emotional responses by providing specific environmental stimuli. Consequently, such a technology could be used to enhance emotion regulation. Thus, people could learn to alter their responses and gradually change their behaviors as they interact with the external world. Emotion regulation is essential to emotional well-being. Emotional dysregulation is a key feature of several affective disorders, such as anxiety and depression. An intervention that fosters emotion regulation ability is important. The feedback system can be considered as a direct way to connect people's inner world and the external environment. Software provides people with visual/aural feedback about emotion and cognition. The brain can then learn to improve management of these states. Classical biofeedback uses a transient dimension, such that one state gives one feedback output. However, emotion perception and response do not necessarily follow a linear path and can be influenced by the preceding emotional state. Moreover, people's cognitive processing mechanisms such as attention and learning, play a role in their emotion regulation ability. These cognitive processes influence the efficiency of using feedback to regulate emo-

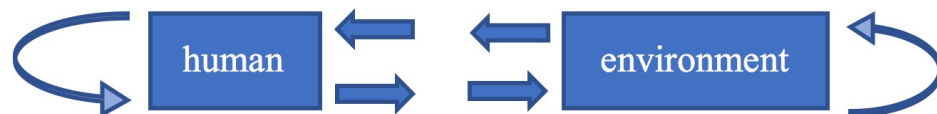


Figure 1.1: Double-dynamic system model.



tion. Therefore, a more integrated and dynamic affective feature is required for emotion detection and regulation than offered by current momentary detection, bio-features. A technology that reflects this more dynamic, integrated interchange between people and the environment could function as an adaptive and intelligent agent, learning to provide dynamic environmental stimuli that affect people over time. To design such an intelligent machine, the first step is to understand how people respond to changing stimuli—the case of real-time interaction (Figure 1.2). The analysis of environmental input and human output can inform us about inner mechanisms related to self-regulation.

## 1.2 Objectives

The temporal dynamics of emotion is well studied in the literature, focusing on changes within a particular stimulus or on the dynamics of brain responses accompanying emotion regulation to a single event. Aspects of each of these temporal dynamics of emotion has also been linked to psychopathology. Few studies have explored the temporal dynamics of stimuli transitions on brain responses linked to emotion regulation. My program of study uses short term changing stimuli (such as stimuli with valence/intensity level shift) as probes to detect their influence on emotional responses. A series of studies are designed to use electrocochleography (EEG) and other psychophysiological meth-



Figure 1.2: Single-dynamic system.

Table 1.1: Factors in the study design.

[Human subsystem]	[Environment subsystem]
Self-rated chronic stress indexes autonomic responses and regulation.	Visual and auditory stimuli.
Executive function indexes effortful, conscious and volitional regulation.	Dynamic stimuli dimensions can include intensity (degree of increase/decrease) or the amount of the change relative to no change.
Cognitive reappraisal and suppression indexes two types of volitional emotional regulation strategies.	Environmental stimuli require focused attention or changes without focused attention.

ods, aimed at extracting EEG features correlated with dynamic emotion underlying self-regulation capacity. A few factors considered in the study design are summarized in Table 1.1.

Several factors in the environment [subsystem] are investigated. The property of the stimuli or the change format of the stimuli is manipulated. The stimuli can be visual or auditory. The intensity /valence of the stimuli either increases or decreases. The stimuli either require participants' attention or do not require focused attention. EEG signals are recorded and analyzed to capture and distinguish participants' responses to static vs dynamic stimuli and to different formats of dynamic stimuli. The different formats of the stimuli aim to induce and elicit brain responses that are sensitive to change. Several factors in the human [subsystem] are also investigated to account for the variance of dy-

dynamic emotional responses that change over time. As emotion and regulation happen simultaneously and unfold over time, one of the important independent variables is individual difference in emotion regulation ability. Self-regulation involves autonomic and unconscious regulation as well as effortful and conscious regulation. The autonomic and unconscious regulation can be measured by self-reported chronic stress scores. The higher the chronic stress, the less capacity and resources to deal with current demands. The effortful and conscious regulation can be measured by self-reported everyday use of cognitive reappraisal and suppression. The more cognitive regulation strategies the person uses, the more capable of processing and restoring from negative and challenging events. In one of the experiments, cognitive reappraisal is also manipulated as an independent variable. Participants are taught to use it when viewing emotional stimuli, with their compared to passive viewing. The next question is: do dynamic stimuli have potential to support self-regulation and recovery from stress? Are the brain responses induced by dynamic stimuli similar to those that occur when positive self-regulation occurs? I hypothesize that the transitional responses might be more directly linked to adaptation and regulation ability. The degree of fluctuation in brain responses to dynamically changing stimuli might be linked to emotion dysregulation. This will be reflected by variable components of EEG responses in different brain regions. dynamic stimuli could be a fast and sensitive probe to detect this kind of dysregulation. Furthermore, if a EEG component is sensitive to dysregulation, effective dynamic stimuli could be applied to alter it. To demonstrate that the EEG responses generate behavioral impacts, subjective ratings, executive function (EF) and other psychophysiological indicators of stress such as skin conductance and heart rate variability will be monitored as well. In sum, the impact of short-term dynamic stimuli

on self-regulation can alter brain activities and behaviors more profoundly than static stimuli (Figure 1.3).

## 1.3 Studies

### 1.3.1 Dynamic visual emotional stimuli $\times$ Chronic stress

The first study compares EEG responses to dynamic vs static visual emotional sequences and their impact on EF, and the potential moderation role of chronic

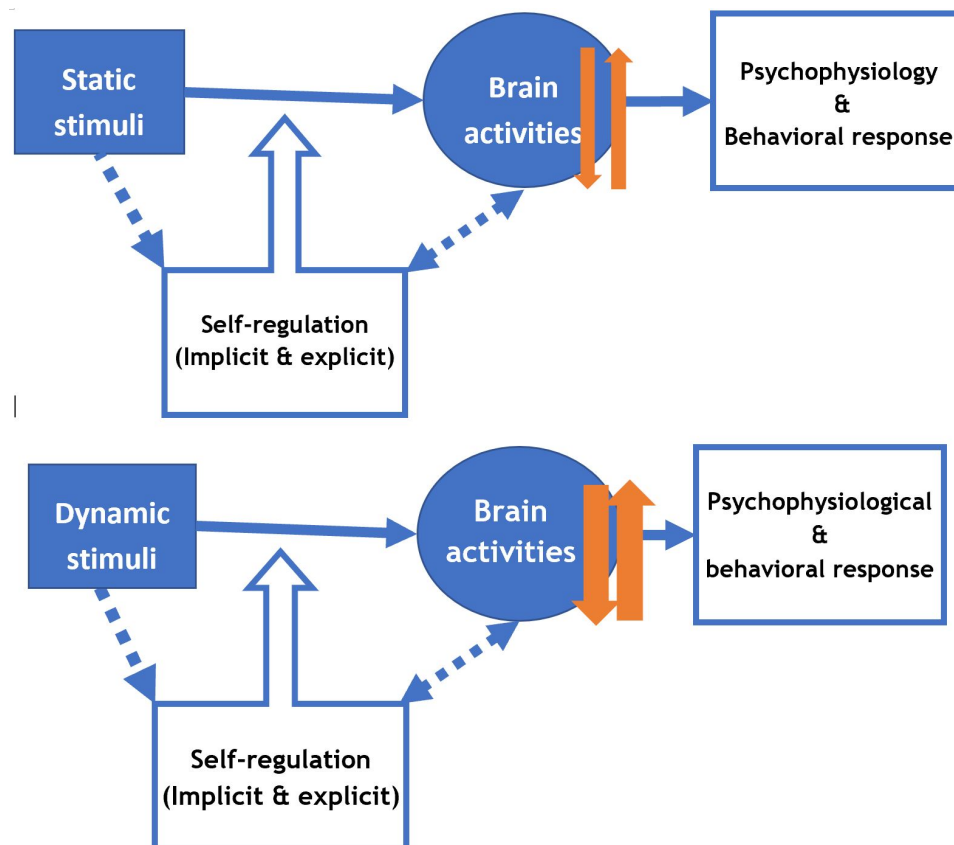


Figure 1.3: Emotion regulation driven by short-term dynamic stimuli hypothesis.

stress. The static emotional sequences comprise of all neutral images or all negative images; whereas the dynamic emotional sequences comprise of two neutral images and two negative images that either increase or decrease in intensity. This study only focuses on negative affect transition. EF is measured by a few trials of flanker task following each image sequence. Because transitions in dynamic sequences require more cognitive resources to process, I hypothesize that EF will be affected more by dynamic sequences. I also hypothesize this relation will be accentuated among chronically stressed individuals. Chronic stress depletes regulatory capacity. This study focuses on the impact of the whole image sequence of static vs dynamic stimulus sequences. Therefore, one of the cortical indexes that represents a period of time could be brain connectivity—the coherence of frontal and parietal regions. Frontal and parietal coherence have been linked to emotion perception and control over emotional experience.

### **1.3.2 Dynamic visual emotional stimuli × Emotion regulation**

The second study adds another predictor—cognitive emotion regulation to assess EEG response to dynamic image sequences. This study only investigates dynamic image sequences and how emotion regulation effort can modulate the dynamic response patterns. Each individual is in two conditions—passive viewing as in study 1 and in a condition where cognitive reappraisal strategy is applied.

In line with the analysis of coherence in study 1, change in coherence within image sequences is another question of interest. EEG frequency band power can be obtained for each image affect category (two images 9 seconds). Thus,

each image sequence has two coherence values. The change of coherence within image affect transition is analyzed within each hemisphere. I hypothesize that individual with more typical use of cognitive reappraisal in their daily lives, will show more flexible neural responses to emotion transitions.

This study focuses on the interaction of stimuli transition, strategy use and subject trait of typical emotion regulation type.

### **1.3.3 Dynamic auditory stimuli × Pre-attentive regulation**

This study examines EEG responses to auditory dynamic stimuli in a passive and pre-attentive manner using a well investigated EEG study paradigm—mismatch negativity (MMN). The MMN protocol requires the subject to ignore infrequently occurring stimuli (oddballs) in a set of frequently occurring stimuli. The fact that MMN does not require a subject's effortful attention allocation is important because it allows us to veritably eavesdrop on the brain without behaviorally engaging it by requiring attention to particular stimuli. Participants are instructed to concentrate on a video of their own choice. Therefore, they do not deliberately pay attention to the audio stimuli played in the background.

This study exhibits a different stimulus changing parameter—standard and deviant trials, as well as dynamic shifts in the intensity of the background auditory stimulus. Thus, this study expands the earlier work in two ways: use of auditory rather than visual stimuli and a focus on unattended environmental stimuli. Even though participants did not have the flanker task or report on emotional affect, I calculate frontal theta-beta ratio and heart-rate variability

that are related to EF and self-regulation, to examine if changes in pre-attentive auditory stimuli could influence EF.

#### **1.3.4 Acute stressor → Dynamic nature sunlight**

This study examines the effect of short-term changes in sunlight in a nature animation following an acute stressor (mental arithmetic). The essence of the study is to examine the therapeutic effect of dynamic stimuli. The first and second studies investigate the brain signature associated with poorer self-regulation; whereas the aim of this study is to alter the adverse effects of stress using dynamic stimuli. The acute stressor also enables me to compare short term to longer term chronic stress effects as examined in the first two studies. Nature scenes are ideal stimuli to be presented dynamically as nature has well documented therapeutic effects. However, whether short term (30 seconds) exposure to dynamic nature scenes produces positive outcomes is unclear. I measure skin conductance to validate the stress induction and analyze alpha and beta band power to indicate relaxation and attention demand during nature animation exposure.

In the four studies described above, coherence and band power are analyzed, compared and contrasted, except for study 3 that also includes event-related potential (MMN). Table 1.2 summarizes each study's basic design. Finding a EEG feature, such as band power in a specific region or combination of regions, could be significant for eventual application in stress reduction and/or emotion regulation protocols. Ultimately this could also be extended to treat affective disorders that share underlying difficulties in emotion regulation. Knowledge about

Table 1.2: Factors in the study design with each study.

[Human subsystem]	[Environment subsystem]
Self-rated chronic stress indexes autonomic responses and regulation <a href="#">Study 1</a> .	Visual stimuli <a href="#">Study 1, 2, 4</a> . Auditory stimuli <a href="#">Study 3</a> .
Executive function indexes effortful, conscious and volitional regulation <a href="#">Study 1, 2, 3, 4</a> .	Dynamic stimuli dimensions can include intensity (degree of increase/decrease) <a href="#">Study 1, 2, 3, 4</a> or the amount of the change relative to no change <a href="#">Study 3</a> .
Cognitive reappraisal and suppression indexes two types of volitional emotional regulation strategies <a href="#">Study 2, 4</a> .	Environmental stimuli require focused attention <a href="#">Study 1, 2, 4</a> or changes without focused attention <a href="#">Study 3</a> .

salient EEG features may provide insights on diagnostics/prognostics and brain functions interacting with dynamic environmental stimuli. Connecting EEG responses from self-regulation effort and stimuli inducement, the bond between the external world and internal world can be enhanced.



CHAPTER 2

**PREFRONTAL-POSTERIOR COUPLING MEDIATES TRANSITIONS  
BETWEEN EMOTIONAL STATES AND INFLUENCES EXECUTIVE  
FUNCTIONING**

*Abstract*

Emotions often result from fluctuating experiences with self-regulation unfolding over time. However, most research has been focused on neural responses to static, affective stimuli. We studied emotion transitions, which correspond to dynamic conditions of varying affective valence or intensities. Functional coupling of prefrontal and posterior cortex (EEG coherence) was recorded during exposure to stable versus changing emotion-eliciting images (static vs. dynamic conditions). Prefrontal-posterior coupling was decreased in the dynamic conditions compared to the static conditions. A decrease in prefrontal-posterior coupling implies less control of the prefrontal cortex over perceptual information, which may allow the brain to become more affected by emotional fluctuations. We also assessed the aftereffect of EEG coherence on executive functioning, utilizing the flanker task. Among individuals reporting higher chronic stress, executive functioning decreased after dynamic conditions. This decrease in executive functioning was mediated by the decrease in prefrontal-posterior coupling in the dynamic conditions. These findings suggest that the strength of prefrontal-posterior coupling is not only related to emotional transitions but also to executive functioning. The deterioration of executive functioning after dynamic emotional processing may reflect the additional cognitive effort required to process dynamic shifts in affective stimuli, and this relationship is exacerbated by chronic stress.

## 2.1 Introduction

Throughout their daily lives, humans continuously interact with a dynamic environment. These dynamic interactions require constant updating of internal representations and respective behavioral adjustments. One important aspect of this constant updating is changes in emotional states. These emotion dynamics not only reflect momentary and transient responses to current stimuli but are also influenced by context and individual differences in self-regulation, which are crucial for psychological health [1, 2, 3].

However, to date, most emotion research has focused on responses to affective stimuli from a static perspective. Little is known about the brain's responses to changing emotional experiences nor how such responses are related to self-regulation mechanisms. Our study investigates hypothesized differences in the brain's responses to static vs. dynamic emotional conditions and their influence on performance in a subsequent executive functioning (EF) task. Because changing stimulation conditions can trigger emotion dynamics [4, 5, 6, 7], in the present study, we define emotion transitions as responses to dynamic stimulation conditions with varying affective valence or intensity, e.g., image sequences with changing valence and/or intensity, as opposed to static conditions without affect transition.

The modulation of emotional responses inherently entails processes of self-regulation. Self-regulation involves a volitional component mediated through EF (working memory operations, behavioral inhibition, and task-switching) as well as a nonvolitional component enabled by autonomous systems [8, 9, 10]. During dynamic changes in the emotional content of our environment, the

residual affective processing from previously experienced emotional stimuli likely affects the perception of current emotional stimuli. Therefore, when emotion transitions occur, it is reasonable to hypothesize that greater EF processing is recruited in the prefrontal cortex (PFC) in order to deal with potentially conflicting responses due to an overlap in incompatible emotions [11]. If this is the case, greater demands upon EF would be expected when individuals are exposed to dynamic as opposed to static emotional stimuli.

Importantly, self-regulation in response to emotional stimuli may be impaired by a large range of factors including, amongst others, chronic stress (e.g. [9]). Chronic stress has well documented effects on behavioral indices of EF [12, 13]. Moreover, at the level of the brain, chronic stress is also known to cause structural and functional changes in areas underlying EF like the PFC and the hippocampus [12, 14, 15, 16, 17]. These chronic stress-induced changes in behavior and brain likely interfere with regulatory functions that facilitate responding to acute demands. As a result, chronically stressed individuals may exhibit more reactive rather than reflective psychophysiological responses, which in turn, place even greater demands on self-regulation [8]. Thus, it may be assumed that dynamic emotional stimuli may result in cumulative aftereffects, which might be different from the effects of purely static negative events on EF. Therefore, investigating the role of chronic stress on EF after emotion transitions may provide important insights on individuals' capability to recruit EF during emotion transitions.

We tested these ideas using a well-established EEG functional connectivity measure: cross-regional cortical synchronization. This measure indexes functional communication among brain areas and is believed to reflect top-down

executive control over incoming perceptual information. Specifically, EEG coherence between prefrontal and posterior cortical regions increases during exposure to emotionally arousing or threatening stimuli, presumably protecting the individual from aversive input [18]. A reduction in EEG coherence between prefrontal and temporoparietal regions may reflect a relative loosening of executive control over the more posterior, predominantly perceptual areas. Research on individual differences in brain responses to affectively laden information has shown that decreased prefrontal-posterior coupling during social-emotional stimulation is related to greater influence of perceptual input on affective states [19, 20, 21, 22, 23, 24, 25, 26, 27]. For example, individuals with high trait rumination exhibited decreased prefrontal-posterior coupling during negative emotional stimulation and the persistence of negative affect was related to the degree of prefrontal-posterior decoupling [26]. Similarly, prefrontal-posterior decoupling is related to the development of intrusive memories in response to viewing negative emotional stimuli [25]. These empirical findings indicate that the investigation of prefrontal-posterior coupling during affective stimulation may provide critical insights on how control and self-regulatory mechanisms undergird emotional processing. As dynamic emotion transitions likely involve the processing of previous stimuli, extending the Papousek and colleagues' findings might be particularly illuminating for understanding self-regulation during dynamic emotional stimulation.

In the present study, participants watched image sequences randomly presented with different patterns (conditions), some of which were static image sequences (all neutral or all negative images), and others which were dynamic image sequences (transition from neutral to negative or vice versa). Immediately after each image sequence, EF was assessed with a flanker task. EEG coherence

was recorded during both emotional stimuli and the flanker task. Considering the EEG coherence findings outlined above [18, 19, 20, 21, 22, 23, 24, 25, 26, 27], we calculated coherence in the beta frequency band ([14 30] Hz). We also specifically investigated beta 1 range ([14 20] Hz), as it has been implicated in higher-level cortical processing (e.g., [28, 29, 30]). We hypothesized that (1), decreased prefrontal-posterior coherence would occur in dynamic emotion transition conditions compared to static emotional conditions. This hypothesis is based on the assumption that dynamic stimuli elicit higher self-regulation demands which consume executive resources, making individuals more susceptible to perceptual input. To corroborate this assumption, we also hypothesized that (2), EEG coherence would mediate the relationship between emotional stimulation and subsequent EF performance. More precisely, we expected that especially in dynamic conditions, decreased prefrontal-posterior coupling would impair performance on the subsequent flanker task and thus reflect the aftereffects of EF resource depletion. (3) This link between EEG coherence, emotional stimulation and EF should be even stronger among individuals experiencing elevated chronic stress, given that their cognitive resources are strained from the beginning.

## 2.2 Methods

### *Participants*

Forty right-handed students from Cornell University were recruited. Informed consent was obtained, and participation was compensated with course credits or \$20 cash. Due to incomplete data, 33 participants were included in the

final sample (51.5% females, age  $M = 22.40$ ,  $SD = 3.80$ ). Exclusion criteria were any open or healing wounds on the scalp, use of any medication that could affect the nervous system and any history of neurological disorders. Participants were requested to refrain from alcohol caffeine, and other stimulants for four hours before the experiment. They were also asked to sleep for at least six hours the night before the experiment. The study was approved by Cornell's Institutional Review Board and was performed in accordance with its guidelines. Informed consent was obtained from all participants.

### *Procedure*

To measure chronic stress, we administered the Perceived Stress Scale (PSS) before EEG recordings [31]. PSS was designed to measure perceived stress level, i.e., unpredictable, uncontrollable, and overloaded. This questionnaire contains 10 items and requires respondents to rate the degree to which situations are appraised as stressful in the last month, such as: "In the last month, how often have you felt confident about your ability to handle your personal problems?" or "In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?" PSS is a reliable and valid instrument for the assessment of perceived stress in college students and workers [32, 33].

Affective state was manipulated by 96 negative, emotionally threatening images (valence:  $M = 2.37$ ,  $SD = 0.65$ , arousal:  $M = 5.95$ ,  $SD = 0.77$ ) and 96 low arousal neutral images (valence:  $M = 5.12$ ,  $SD = 0.53$ , arousal:  $M = 3.17$ ,  $SD = 0.66$ ) selected from the IAPS database [34]. Four images, each lasting 4500 ms, were presented one by one as an image sequence. As Figure 2.1 shows, four different types of image sequences were defined as experimental conditions. For static conditions, the sequences consisted of all neutral (static-neutral) or all

negative (static-negative) images, which appeared 6 times each. For dynamic conditions, the first two images and the last two images were from the same affect category, either neutral or negative; therefore, the transition occurred at the third image. The images either transitioned from neutral to negative (dynamic-increase) or from negative to neutral (dynamic-decrease), which appeared 18 times each. The image sequences of all conditions were randomly presented with no image repetition to participants. Due to the randomization of dynamic and static conditions and more image sequences of dynamic conditions, the paradigm was more authentic in terms of real-life emotional processing. To counteract the balance of the amount of image sequence between static and dynamic conditions, we selected 6 sequences in dynamic conditions that were next to the static conditions. These were distributed across the experiment.

Immediately after each sequence, 12 trials of the flanker task [35] each 1200

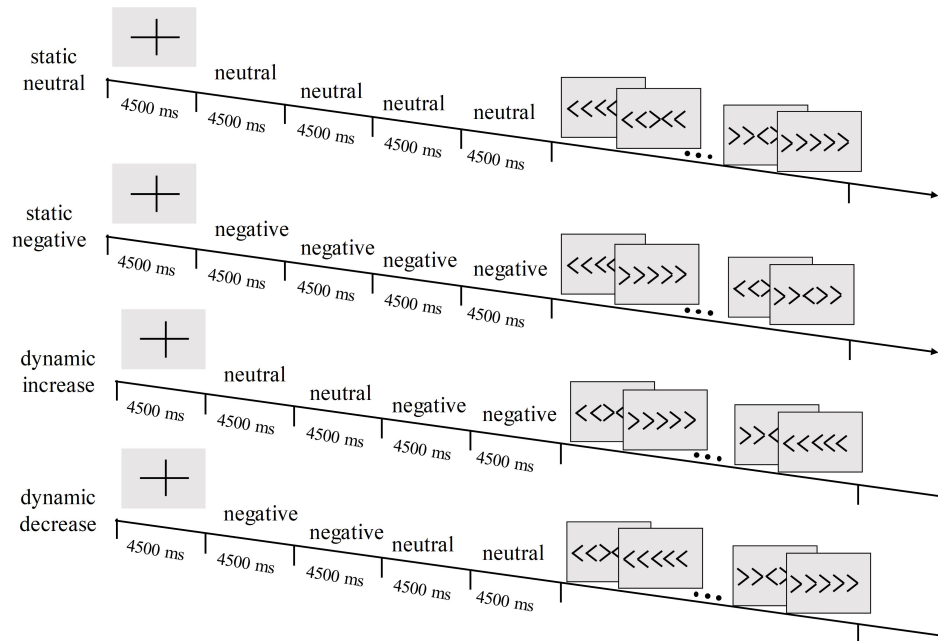


Figure 2.1: Schematic representation of the four image sequence conditions directly followed by the flanker task.

ms (stimulus 200 ms and response window: 900, 1000 or 1100 ms) were presented to assess EF performance [36]. In the flanker task, a visual array of flag stimuli with the middle flag randomly surrounded by flags in the same direction (congruent) or in the opposite direction (incongruent). Participants responded to the direction of the middle flag as quickly and accurately as possible.

### *EEG Recording and Processing*

EEG was recorded from a 128- channel BioSemi EEG device with digital sampling rate at 512 Hz. All EEG channels were referenced offline to the algebraic average of left and right mastoids and notch filtered (55~65 Hz) to remove power-line noise. EEG signals were bandpass filtered between 1~40 Hz, using a two-way least squares finite impulse response filter in EEGLab [37]. Bad channels were identified and spherically interpolated. Then the data were epoched from 4 seconds before and 35 seconds (total image sequence and flanker task duration) after the sequence onset. Each epoch was visually inspected. Those epochs with obvious abnormal signal segments, such as head movement, were excluded for Independent Component Analysis (ICA). Then the extended Infomax ICA [38], which was implemented in EEGLab as the default ICA algorithm, was utilized to detect and remove artifact contaminated by eye movements, muscle, and cardiac artifacts. We determined the ICA components by the ICA maps and also the power spectrum of the ICA component [37]. After removing the artifact components, the ICA source signals were transferred back to the original signal space, which was then used for the subsequent analysis.

The first half second of affective image viewing (0 to 500 ms) was removed from analysis to eliminate sensory transition effect. The average number of artifact-free seconds per participant was  $M = 79.90$  ( $SD = 4.61$ ),  $M = 79.80$  ( $SD =$



4.39),  $M = 238.4$  ( $SD = 11.80$ ) and  $M = 239.2$  ( $SD = 9.20$ ) for conditions of static-neutral, static-negative, dynamic-increase and dynamic-decrease respectively. There was no significant difference in the time length between static conditions ( $p = .910$ ), and between dynamic conditions ( $p = .720$ ).

Coherence measures the degree of covariance between two spatially distinct signals in prefrontal and posterior regions. We applied the magnitude-squared coherence, which was calculated by the cross-spectrum divided by the product of the auto-spectrum of the two signals. This measure includes information on the amplitude and phase. Electrodes distance is a factor that influences the effect of volume conduction. The spatial resolution of EEG is approximately 5 cm [39], and the optimal distance between electrodes must be around 10–20 cm in human EEG-recordings to minimize the effect of volume conduction [40, 41]. We confined our analyses to electrode pairs located no less than ~18 cm from each other to minimize the effect of volume condition. Following Miskovic and Schmidt (2010), four clusters of electrodes were selected, with right frontal C16, C10, C7; left frontal C29, C32, D7; right parietal B4, B11, A28; left parietal A7, D31, A15. Coherence scores of nine electrode pairs each were averaged to summarize interactions within the different brain regions respectively as shown in Figure 2.2 (right hemisphere: C16-B4, C16-B11, C16-A28, C10-B4, C10-B11, C10-A28, C7-B4, C7-B11, C7-A28; left hemisphere: C29-A7, C29-D31, C29-A15, C32-A7, C32-D31, C32-A15, D7-A7, D7-D31, D7-A15). We calculated coherence throughout the image sequence (18000 ms) and then averaged all sequences for each condition.

Following the methods described in Miskovic and Schmidt [18], artifact-free EEG data were submitted to a discrete Fourier transform with a Hamming win-

dow of 2000 ms width and 50% overlap, and Welch's method was used to estimate the auto spectrum of itself and cross-spectrum between two signals. The cross-spectral coherence between two channels was calculated using the following formula in 2.1. (Note:  $S_{xy}$  denotes the cross-spectrum,  $S_x$  and  $S_y$  denotes the auto-spectrum; The  $E$  denotes the expectation across the repeated sequences). The coherence in beta frequency band ([14 30] Hz) and beta 1 frequency band ([14 20] Hz) were calculated throughout the image sequence (18000 ms) and then averaged all sequences for each condition.

$$R_{xy}(f)^2 = \frac{E[S_{xy}(f)^2]}{E[S_x(f)] \times E[S_y(f)]} \quad (2.1)$$

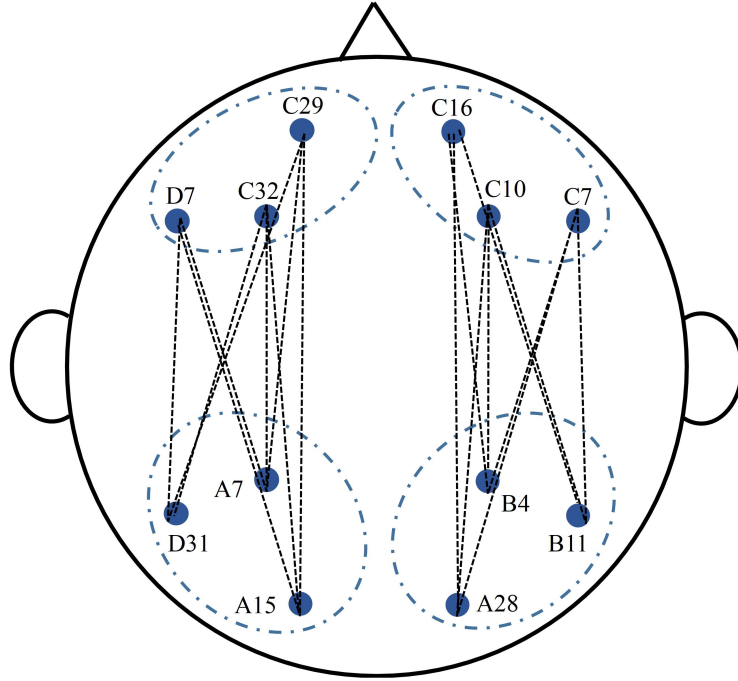


Figure 2.2: The electrodes used in the present study. Four clusters of electrodes were selected, with right frontal C16, C10, C7; left frontal C29, C32, D7; right parietal B4, B11, A28; left parietal A7, D31, A15. The dashed lines between electrodes represent functional connectivity

### *Statistical analysis*

We applied linear mixed effect models so that each individual was modeled as a random effect. We first used four experimental conditions to predict EEG coherence, and then reran the model with grouped static vs. dynamic conditions. Separate models were applied for each hemisphere. Since previous research revealed right hemisphere dominance in coherence changes during emotional processing, a priori, planned comparison was conducted on static-neutral vs. static-negative in the right hemisphere to test if our paradigm could replicate previous findings [18].

Before we explored the image sequence condition effect on subsequent EF and the mediation role of EEG coherence, we predicted flanker reaction times (RTs) by image sequence conditions. Then RTs were predicted by coherence. Chronic stress was added as an interaction term with image sequence conditions. High and low chronic stress are plotted  $\pm 1$  SD from the mean for descriptive purposes only in the Figures. Inferential analyses maintained the continuous nature of the chronic stress variable.

Flanker performance was calculated as RTs on incongruent trials, with RTs on congruent trials as a covariate. Trials with inaccurate responses or outlier RTs were deleted (3.14% of trials). We found that the first half of flanker trials (6 trials) followed by each image sequence had a stronger interaction effect with chronic stress while the effect decayed at the end given temporal separation from the emotional stimuli. Thus, we used the initial six flanker trials following the emotional stimuli in the following analysis.

## 2.3 Results

### *Coherence in Static vs. Dynamic Conditions*

We first examined the effect of static and dynamic image sequence conditions on EEG prefrontal-posterior coherence. Image sequence conditions significantly affected coherence in beta 1 range [14 20] Hz and beta range [14 30] Hz ( $p < .001$ ). Yet, only beta 1 coherence mediated the relationship between the image sequence conditions and subsequent measures of EF. For this reason, our report will focus on beta 1 coherence only. As shown in Figure 2.3 (a-b), significant effects of image sequence condition on beta 1 coherence were observed in both hemispheres (right hemisphere,  $F(3, 96) = 13.00$ ,  $p < .001$ , proportion change of variance (PCV) = 26.7%; left hemisphere,  $F(3, 96) = 7.22$ ,  $p < .001$ , PCV = 15.9%). Planned comparisons indicate that beta 1 coherence was higher during the threatening static-negative than during the static-neutral stimulus in the right hemisphere (pairwise comparison: Estimate = 0.0146, S.E. = 0.0066,  $p < .05$ ).

Combining the static conditions together and comparing them to the combined dynamic conditions, significantly lower coherence in the dynamic vs the static conditions was observed in both hemispheres (right hemisphere,  $F(1, 98) = 28.49$ ,  $p < .001$ , PCV = 21.7%; left hemisphere,  $F(1, 98) = 18.26$ ,  $p < .001$ , PCV = 14.9%). Table 2.1 shows statistics of beta 1 coherence

There were no main or interactive effects of chronic stress on coherence. Chronic stress ( $M = 15.91$ ,  $SD = 6.33$ ) was also unrelated to flanker performance ( $F(24) = .73$ ,  $p = .40$ ) or frontal-posterior coherence ( $F(31) = 3.00$ ,  $p = .09$ ).

Table 2.1: Estimates (standard errors) of static condition vs. dynamic condition. There were no main or interactive effects of chronic stress ( $M = 15.91$ ,  $SD = 6.33$ ) on coherence. Chronic stress was also unrelated to flanker performance ( $F(24) = 0.73$ ,  $p = 0.40$ ) or frontal-posterior coherence ( $F(31) = 3.00$ ,  $p = 0.09$ ).

	Condition		
	Static	Dynamic	Dynamic-Static
Right hemisphere 95% CI	0.12 (0.01) [0.10, 0.14]	0.14 (0.01) [0.12, 0.16]	-0.02 (0.00)
Left hemisphere 95% CI	0.12 (0.01) [0.10, 0.14]	0.13 (0.01) [0.11, 0.15]	-0.01 (0.00)

### *Coherence as a Mediator of Condition Effects on Flanker*

We next evaluated the mediating role of coherence on the relationship between emotional stimuli and executive functioning. Before testing mediation, we examined how coherence influenced flanker performance (congruency effect). Coherence interacted with chronic stress on subsequent flanker performance in both hemispheres (right,  $F(1, 53) = 17.70$ ,  $p < .001$ ,  $PCV = 15.6\%$ ; left,

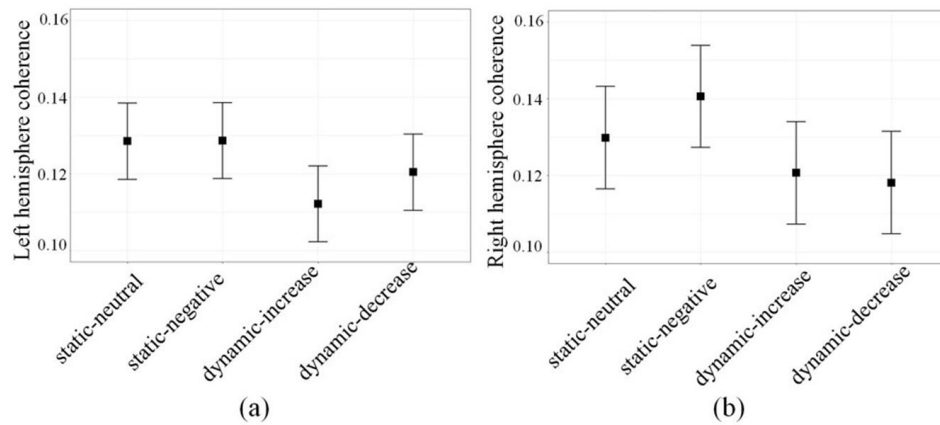


Figure 2.3: Beta 1 frequency range prefrontal-posterior coherence of four image sequence conditions in left (a) and right (b) hemispheres. Error bars are standard errors

$F(1, 64) = 10.99, p = .002, PCV = 7.0\%$ ). Under high chronic stress, decreased coherence during image sequences led to worse flanker performance, whereas increased coherence facilitated flanker performance (see Figure 2.4 (a)).

Coherence during image sequence was highly correlated to coherence during the flanker task ( $r = 0.90, t(130) = 24.16, p < .001$ ). Furthermore, coherence during the flanker task interacted with chronic stress on flanker performance in the right hemisphere ( $F(1, 68) = 4.89, p = .030, PCV = 16.9\%$ ). Left hemisphere coherence was not significantly affected ( $F(1, 79) = 0.24, p = .63$ ). Under high chronic stress, lower coherence during the flanker task led to worse flanker performance, whereas higher coherence facilitated flanker performance (see Figure 2.4 (b)).

The effect of static vs. dynamic emotional conditions on flanker performance was mediated by beta 1 coherence, but only in participants reporting high chronic stress (above the mean) (Figure 2.5). In the right hemisphere, the indirect path was  $ab = 7.91$ , with a standard error of 3.20 ( $p = .013$ ); in the left

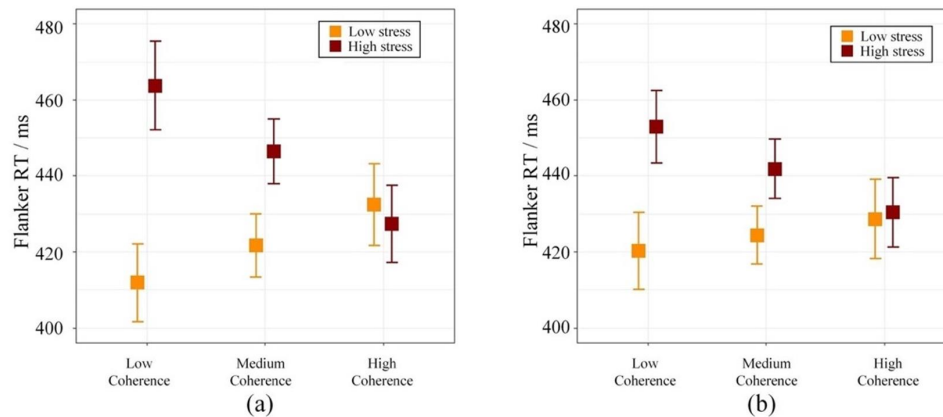


Figure 2.4: Flanker RTs (congruency effect) by prefrontal-posterior beta 1 coherence during image sequence (a) and flanker task (b) in the right hemisphere.

hemisphere, the indirect path was  $ab = 5.01$ , with a standard error of 2.48 ( $p = .044$ ). In participants high in chronic stress, the dynamic conditions evoked lower coherence, which led to slower reaction times (RTs).

## 2.4 Discussion

The present study investigated prefrontal-posterior coupling during exposure to both static and dynamic affective image sequences and its link to executive functioning. Decreased coupling between prefrontal and posterior cortical regions was observed during emotion transitions regardless of affect (neutral or negative) and also impaired subsequent executive functioning. However, this effect only occurred among individuals high in chronic stress. Furthermore,

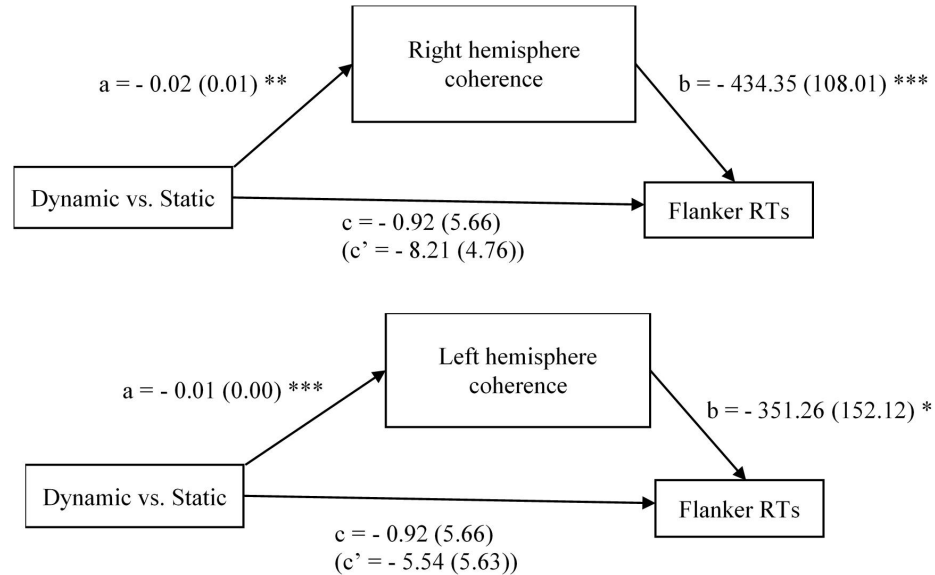


Figure 2.5: Mediation results—beta 1 frequency range prefrontal-posterior EEG coherence mediates the effects of emotion stimulation conditions on flanker RTs. Estimates (standard errors), \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

the apparent adverse impact of processing dynamic emotion stimuli on EF was mediated by EEG coherence in beta 1 range ([14-20] Hz) during image viewing.

Our data replicate prior research showing that negative stimuli can elevate prefrontal-posterior beta coherence [18], but this is the first demonstration that beta ([14-30] Hz), including beta 1 range ([14-20] Hz) coherence is related to emotion transitions. Decreases in prefrontal-posterior EEG beta coherence induced by emotional stimulation reflect a decrease in the prefrontal cortex's regulatory control over parietal regions [21, 22, 23, 24, 25, 26]. Therefore, beta coherence plays a critical role in brain responses to emotion-cognition interaction.

In the present study, we interpret the changes in prefrontal-posterior coupling during dynamic sequences as a neural correlate for self-regulation. In line with this interpretation, our results showed that EF was hindered immediately after exposure to dynamic emotional image sequences. While only constituting indirect evidence, this finding suggests that emotion transitions elicit increased self-regulation demands, which occur at the expense of other executive functioning, the aftereffects of which may be visible in impaired performance in the subsequent flanker task. Importantly however, this effect was only found in participants reporting high chronic stress. Accordingly, it appears that people with chronic stress are more vulnerable in contexts demanding self-regulation. One possible mechanism for this relationship is that residual emotion from preceding images might generate emotional conflicts, mobilizing more executive control mechanisms for self-regulation in order to manage the conflicting emotional stimuli. It also makes sense that chronically stressed individuals might be less able to manage conflicts [42], given already impaired attentional control [17]. This also appears to diminish at least short term EF capacity as indexed by



slower reaction times in the flanker task in the present study [9, 43].

Importantly, our study calls attention to the mediating role of brain synchronization in the relationship between emotion transitions and EF. The reduced coherence evoked by emotion transitions continued during the flanker task, which suggests that individuals reporting high chronic stress were vulnerable to high demands for attentional allocation during emotional image viewing. This is consistent with prior work showing that chronic stress disrupts functional connectivity within the frontoparietal network that mediates attention shifts [17]. Another possible explanation is that the reactive rather than reflective disposition of those with high chronic stress levels may have weakened prefrontal cortical regulation of amygdala responses [44]. This might sustain experiences of emotion in the absence of an emotional stimulus. Note that the significant mediation effect was found only with beta 1 coherence but not the entire beta range, which might be age-related [45], as our participants were all college students.

The primary limitations of the current study are that the duration of the induced drop in EF performance is unknown because only a limited number (6) of flanker trials were used to test for aftereffects. It is also unknown whether other negative emotional sequences would create similar results. A valuable extension of this study would be to examine individuals with self-regulatory difficulties, for instance, individuals with anxiety disorders. Several strands of evidence show that PFC dysfunction reported in mental disorders such as depression or anxiety, manifests in diminished attentional/inhibitory control during cognitive tasks and sustained negative affect processing [46, 47, 48, 49]. Moreover, evidence of EEG prefrontal-posterior coherence reduction during

emotional perception also comes from studies on individuals with schizotypal [22] and individuals with gelotophobia with/without schizophrenia spectrum/social phobia [21]. Understanding brain response to emotion transitions may inform our understanding of the cognitive capacity required to regulate and control emotional episodes. Hence, studies manipulating self-regulation capability by EF training [9, 50] or cognitive reappraisal [51] under emotion transition events are needed.

More speculatively, the changes in brain activity uncovered in the present study might explain why exposure to fluctuating emotional context, be it positive or negative, correlates with poorer psychological health [52]. In this respect, it may be helpful to extend investigations of neural substrates underlying dynamic emotion transitions to other dynamics, such as other valence changes, or multiple transitions within one affect stimulation. In addition, the right and left hemisphere exhibited different coherence pattern across four conditions (Figure 2.3). Additional work should investigate neural response changes during dynamic conditions in each hemisphere. Such endeavors could inspire more complex models of the neurodynamic of emotions and may also facilitate insights on neurocognitive markers of psychiatric disorders [53].

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CHAPTER 3

**NEURAL PROCESSING DURING DYNAMIC EMOTIONAL  
EXPERIENCES: THE ROLE OF COGNITIVE REAPPRAISAL STYLE AND  
STRATEGY USE**

*Abstract*

Coping with fluctuating events in everyday life is vital to well-being. Because previous context and regulatory effort may influence current emotional experience, studying emotion transitions may reveal additional insights into the neurocognitive architecture of emotion regulation. Though the neural substrates of emotion regulation have been extensively studied, it is not known how they operate during emotion transitions. In our current study, participants watched emotional image sequences that either changed from neutral to negative or from negative to neutral. They either passively watched the emotion sequences or cognitively reappraised the sequences to reduce negative affect. We also assessed individual differences in cognitive reappraisal style. We modeled the interaction of cognitive reappraisal style, affect stimuli transitions (first and last images), and cognitive/regulatory strategies (watch vs. reappraisal task) on EEG prefrontal-posterior coherence. Prefrontal-posterior alpha coherence was influenced by dynamic emotional transitions (negative → neutral; neutral → negative) for people who more typically utilize cognitive reappraisal. Beta coherence change, on the other hand, was influenced by cognitive reappraisal effort for people with less habitual reappraisal style. The coordinated yet complementary functions of alpha and beta coherence during emotion transitions may help us draw a more complete picture of neural activity during emotion dynamics and regulation. Maladaptive emotion regulation might be associated

with inflexible neural responses during dynamic changes in emotional experiences. Brain responses to dynamic stimuli may reflect self-regulation capacity specifically and coping skills more generally. Formalizing temporal neurodynamic of emotion requires consideration of personal characteristics, situation factors, and cognitive/regulatory strategies.

### **3.1 Introduction**

Why some people are better able to flexibly regulate emotion in response to concurrent environmental experience, and others are susceptible to previous emotional interference is a central question in emotion research. Humans continuously interact with the dynamic social and physical environment with emotions unfolding over time. Dynamics of emotion may be critical to infer emotion regulation flexibility, adaptation to environmental fluctuations, and psychopathology [1, 2, 3, 4]. The neural substrates of temporal dynamics of emotion have been investigated primarily in response to a single event [5, 6, 7, 8]. Yet, coping with shifting emotional experiences is a common fact of life, but its neural substrates have not been well studied. Different from a momentary emotional response, an emotional transition is a movement between emotional states. The present study examines neural mechanisms underlying dynamics of emotion, i.e., emotion transitions, induced by dynamic shifts in affective stimuli. We also investigate how these mechanisms operate as a function of emotion regulation in situ and in relation to individual differences in habitual cognitive reappraisal strategy use.

Several studies have demonstrated that previous emotional context influences emotional perception and neural responses [9, 10, 11, 12, 13]. For exam-

ple, perception of neutral images is more negative if they are preceded by negative images than preceded by non-negative images. The previous reappraisal can also modulate emotional processing [14]. If contextual factors such as prior emotional state are critical, it remains important to study neural activity to specific emotional stimuli as a function of prior emotional experiences. The perceptual input in the situational context influences emotion as bottom-up processes, but its interaction with top-down processes situated in higher-order cortical functions is also important in emotion transitions. One of the most effective top-down processes is cognitive reappraisal, which is an antecedent-focused strategy of emotion regulation involving the attempt to alter the emotional meaning of originally salient stimuli [15, 16]. An example of reappraisal might be thinking an aversive situation will eventually become better. Cognitive reappraisal reflects a form of cognitive control based in the prefrontal cortex (PFC) that regulates activations in ventral emotion generative regions [17]. While prior work has made significant contributions in characterizing reappraisal's neural mechanisms and behavioral outcomes, this work has primarily been confined to a single type of affective stimuli without considering context changes. Yet, emotional experiences often unfold over time proximate to multiple emotional stimuli.

Furthermore, if context can modulate the intensity of a negative emotional experience, are people able to execute cognitive reappraisal procedures to deal with increasing demand? The degree of coupling between prior and current emotional stimuli likely varies with individual differences in habitual use of cognitive reappraisal. Both instructed reappraisal and habitual use of reappraisal are manifested in similar neural substrates—decreased amygdala activity and increased prefrontal control activity [18]. Individuals with less habitual

use of reappraisal tend to have ineffective regulation towards negative events and may be more likely to exhibit inflexible neural responses when emotional contexts change. Therefore, emotion regulation is inherently an interaction of person (i.e., trait-like), strategy (i.e., reappraisal), and situation (i.e., context) factors [19, 20, 21]. The interaction of these three factors is fundamental to understanding the temporal dynamics of emotional processing. Examination of the neurobiological basis of individual differences related to emotional transition and regulation strategies might help to explain why some individual have greater difficulties with environmental fluctuations.

Thus, the overall goal of our study is to examine emotion transitions induced by context change and the modulating role of habitual and instructed cognitive reappraisal. We used dynamic shifts in affective stimuli—image sequences with changing valence and intensity (i.e., neutral and negative) to ensure robust modulation of neural coherence. We manipulated cognitive reappraisal strategy during task presentation and assessed individual differences in habitual cognitive reappraisal strategy use. We model emotion dynamics reflected by EEG prefrontal-posterior coherence. The functional coupling of prefrontal and posterior cortices has been extensively studied on emotional perception and individual differences in regulatory control [22, 23, 24, 25, 26, 27, 28, 29, 30]. In particular, this functional coupling also relates to emotion transitions during dynamic shifts in affective stimuli [31]. This pattern of results suggests that top-down executive functioning becomes more engaged in processing incongruent emotional information during emotion transitions. Furthermore, this top-down executive functioning may also reflect individual differences in emotion regulation styles or traits. Extending these findings to coherence response during context changes might be particularly illuminating for understanding individ-

ual differences in the dynamics of emotion.

Though primarily found in the beta-band (14-30Hz) oscillation coupling between the frontal and parietal regions in emotion research [23, 24, 25, 26, 27, 28, 29, 30], it would be also valuable to examine the alpha-band (8-13Hz) oscillation coupling because alpha-band oscillation is related to cognitive functions [32], such as inhibition [33]. We hypothesized that individuals who generally rely less on cognitive reappraisal would be vulnerable when processing conflicting emotional content. Such individuals would have inflexible/maladaptive changes in EEG prefrontal-posterior coherence when emotional stimuli change. We also hypothesized that coherence change would be different in the reappraisal in comparison to the passive, watch condition because of emotion transition.

## 3.2 Methods

### *Participants*

Thirty-six students from Cornell University participated in this study. Due to incomplete data or equipment malfunction, 31 participants remained for the final sample (female 70%, age  $21.5 \pm 3.5$  years). Participants were requested to refrain from alcohol, caffeine, and other stimulants for four hours before the experiment. They were also asked to sleep for at least six hours the night before the experiment. Participation was compensated with course credit or \$20. Cornell's Institutional Review Board approved the study. Informed consent was obtained from all participants.

## *Study Design*

Negative, emotionally threatening images (valence:  $M = 2.37$ ,  $SD = 0.65$ , arousal:  $M = 5.95$ ,  $SD = 0.77$ ) and low arousal neutral images (valence:  $M = 5.12$ ,  $SD = 0.53$ , arousal:  $M = 3.17$ ,  $SD = 0.66$ ) were selected from the IAPS database [34]. Each image sequence comprised of 4 images, 4500 ms duration per image. As Figure 3.1 shows, two different types of image sequences with transitions between two affect types were defined as experimental conditions. Image sequences contained images either transitioning from neutral to negative (i.e., neutral- $\rightarrow$ negative, 36 trials) or from negative to neutral (i.e., negative- $\rightarrow$ neutral, 36 trials). When viewing each image sequence, participants were instructed to either passively watch each image sequence or cognitive reappraise each image sequence. For each image sequence condition, there were 18 reappraisal task trials and 18 watch task trials. The screen showed the words "watch" or "reappraisal" for 2000 ms before each image sequence. In the watch task, participants were instructed to observe the stimulus image and experience whatever feeling/emotion the image evoked without trying to change or alter their emotions. The reappraisal task required participants to re-interpret the meaning of the images so that their negative affect was decreased by (i) transforming the depicted scenario into something less negative or into positive terms (e.g., a man sitting on a bench alone with bowed head because he is taking a nap and waiting for his wife), or (ii) rationalizing and objectifying the content of the picture (e.g., an image of a glass with blood and tissue was a scene from a movie). During the practice session, participants were asked to go through the cognitive reappraisal procedure out loud. They were assisted if their strategies were assessed as inappropriate by the experimenter. The image sequences of both conditions, and both tasks were randomly presented with no image repetition within the partic-

ipant. Both EEG and fMRI emotion regulation studies have demonstrated that this randomized task manipulation effectively distinguishes neural responses between the watch and reappraisal tasks (e.g., [35, 8]).

In our study, because we have four, back-to-back images presented, participants did not have time to rate every image after its presentation for us to validate reappraisal task manipulation. Moreover, rating each image during presentation might interfere with ongoing emotion regulation. We validated the reappraisal task manipulation using the same sequential protocol in pilot study (N = 10, female 50%, age M = 21 years) collecting only subjective ratings (0 = neutral to 4 highly negative) after each image sequence. Cognitive reappraisal significantly reduced the negative emotional valence of the image sequence ( $p < .001$ ). In the formal study, we did not include subjective rating after each image sequence for reasons outlined above. Instead, between each image sequence, there were 16 trials of the flanker task (stimulus 200 ms and response window: 900, 1000 or 1100 ms) designed as a distraction to eliminate residual emotional

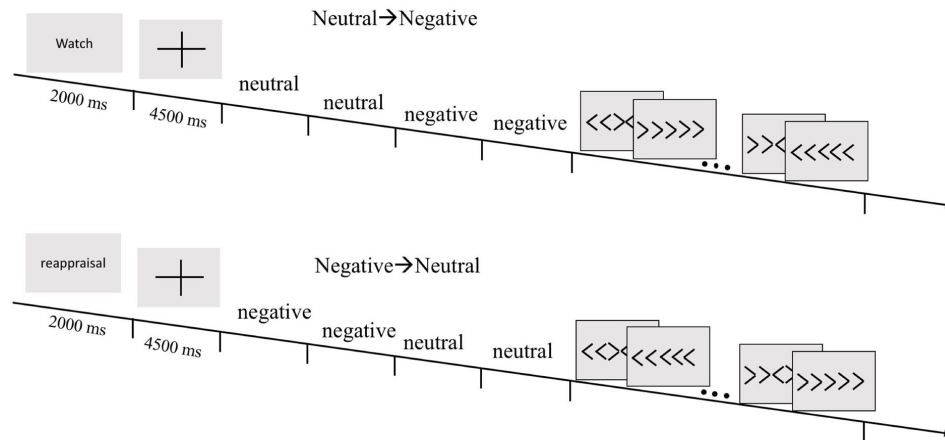


Figure 3.1: Schematic representation of the two image sequence conditions and watch vs. reappraisal tasks.



influence.

To assess individual differences in the tendency to use cognitive reappraisal in the face of negative emotions, we administered the Emotional Regulation Questionnaire (ERQ) [36] before the experiment. Six items measure cognitive reappraisal with questions like: “When I want to feel less negative emotion (such as sadness or anger), I change what I’m thinking about.” or “When I want to feel more positive emotion (such as joy or amusement), I change what I’m thinking about.” The ERQ has sound psychometric properties across a wide range of samples [37, 38, 39].

### *Data Recordings*

A 128- channel BioSemi EEG device was used to record EEG at 512 Hz sampling rate. In the EEG preprocessing procedure, all EEG channels were first referenced to the algebraic average of left and right mastoids. Then EEG signals were bandpass filtered between 1~40 Hz, using a two-way least-squares finite impulse response filter in EEGLab [40]. Bad channels were visually identified and spherically interpolated. Next, the data were epoched by each image. Those epochs with obvious abnormal signal segments were excluded for Independent Component Analysis (ICA). Then the extended Infomax ICA [41], which was implemented in EEGLab as the default ICA algorithm, was utilized to detect and remove artifact contaminated by eye movements, muscle, and cardiac artifacts. We determined the ICA components by the ICA maps and also the power spectrum of the ICA component [40]. After removing the artifact components, the ICA source signals were transferred back to the original signal space, which was then used for the subsequent analysis.

Coherence measures the degree of covariance between two spatially distinct signals in prefrontal and posterior regions. The spatial resolution of EEG is approximately 5 cm (Nunez, 1995), and the optimal distance between electrodes must be around 10–20 cm in human EEG-recordings to minimize the effect of volume conduction [42, 43]. We confined our analyses to electrode pairs located no less than 18 cm from each other to minimize the effect of volume condition. The same as previous study [31], four clusters of electrodes were selected, with right frontal C16, C10, C7; left frontal C29, C32, D7; right parietal B4, B11, A28; left parietal A7, D31, A15. Coherence scores of nine electrode pairs each were averaged to summarize interactions within the different brain regions respectively as shown in Figure 3.2 (right hemisphere: C16-B4, C16-B11, C16-A28, C10-B4, C10-B11, C10-A28, C7-B4, C7-B11, C7-A28; left hemisphere: C29-A7, C29-D31, C29-A15, C32-A7, C32-D31, C32-A15, D7-A7, D7-D31, D7-A15).

Artifact-free EEG data were submitted to a discrete Fourier transform with a Hamming window of 2000 ms width and 50% overlap, and Welch’s method was used to estimate the auto spectrum of itself and cross-spectrum between two signals. The cross-spectral coherence between two channels was calculated using the following formula in (1). (Note:  $S_{xy}$  denotes the cross-spectrum, and  $S_{xx}$  and  $S_{yy}$  denote the auto-spectrum; The  $E$  denotes the expectation across the repeated sequences). The coherence in the alpha frequency band ([8 13] Hz) and the beta frequency band ([14 30] Hz) were calculated. The first half-second of each image viewing (0 to 500 ms) was removed from analysis to eliminate sensory transition effect. We calculated coherence for the first two and last two images in each image sequence and then averaged them for each image sequence condition. For each person, we computed the average coherence value of the first two and last two images in each image sequence condition under each task.

## Data Analysis

We designed this experiment to test if EEG coherence induced by the dynamic shifts in affective stimuli would interact with the experimental manipulation of task (cognitive reappraisal vs. watch) as well as with individual differences in habitual reappraisal. Previous work on EEG prefrontal-posterior coherence has shown that right hemisphere beta coherence is associated with emotional perception and regulation ability. Therefore, we only modeled coherence in the right hemisphere. To examine the coherence in emotional image change, task, and individual differences, linear mixed-effects models including order (first two, last two) and task (watch, reappraisal) as within-subject fac-

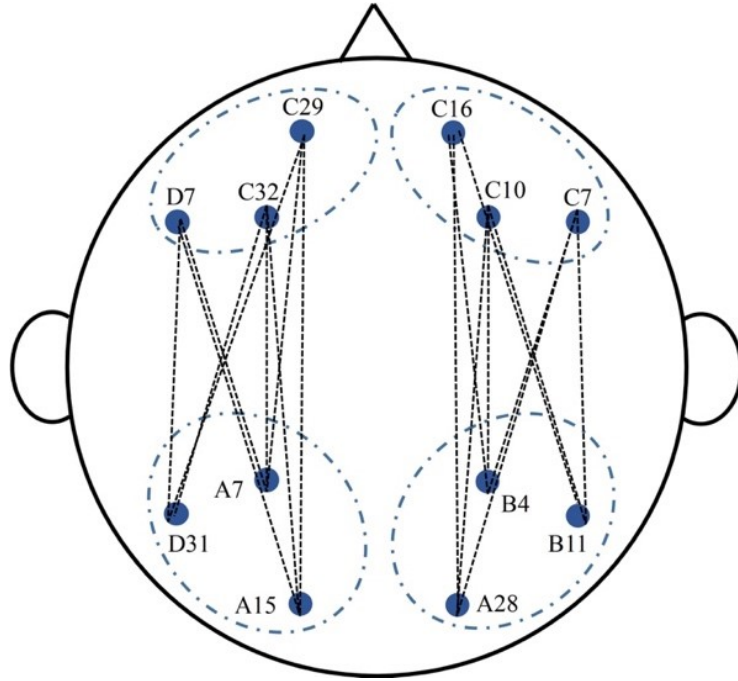


Figure 3.2: The electrodes used in the present study. Four clusters of electrodes were selected, with right frontal C16, C10, C7; left frontal C29, C32, D7; right parietal B4, B11, A28; left parietal A7, D31, A15. The dashed lines between electrodes represent functional connectivity.

tors and habitual reappraisal style (low-high, continuous variable,  $M = 4.46$ ,  $SD = 1.31$ ) as a between-subject factor were conducted on the dependent variable of EEG coherence for neutral→negative and negative →neutral conditions respectively. We also tested alpha and beta band separately. Bonferroni correction was performed for statistical critical value correction; therefore, the critical value alpha was set at 0.0125. Any significant effect after correction is marked with an asterisk \* below. High and low reappraisal style are plotted  $\pm 1$  SD from the mean for descriptive purposes only in the Figures. All inferential analyses maintained the continuous nature of individual differences in typical use of cognitive reappraisal.

### 3.3 Results

#### *Beta coherence changes during emotion transition*

When images transitioned from neutral to negative, the interaction of order  $\times$  task  $\times$  reappraisal was significant (before critical value correction) for beta coherence,  $\chi^2(1) = 4.78$ ,  $p = 0.029$  (Figure 3.3 A & B). The beta coherence change pattern varied according to individual habitual reappraisal style and the pattern reversed between the watch and reappraisal task condition, respectively. When images transitioned from negative to neutral, the interaction of order  $\times$  task  $\times$  reappraisal was not significant in beta coherence,  $\chi^2(1) = 1.55$ ,  $p = 0.2126$ , but the interaction of order  $\times$  task emerged marginally significant (before critical value correction),  $\chi^2(1) = 3.4498$ ,  $p = 0.063$  (Figure 3.3 C & D).

#### *Alpha coherence changes during emotion transition.*

When images transitioned from neutral to negative, although the three-way interaction of order x task x reappraisal was not significant in alpha coherence,  $\chi^2(1) = 0.00$ ,  $p = 0.996$ , if we reduced the model to a two-way interaction, order x task was significant,  $\chi^2(1) = 7.23$ ,  $p = 0.0071^*$  (Figure 3.4 A & B). This means that during the watch task, alpha coherence decreased, while during the reappraisal task, it increased regardless of participants' habitual reappraisal style. When images transitioned from negative to neutral, the interaction of order x task x reappraisal was significant in alpha coherence,  $\chi^2(1) = 9.971$ ,  $p = 0.00159^*$  (Figure 3.4 C & D). The alpha coherence change pattern varied according to individual differences in habitual reappraisal and the pattern reversed between the watch and reappraisal task condition.

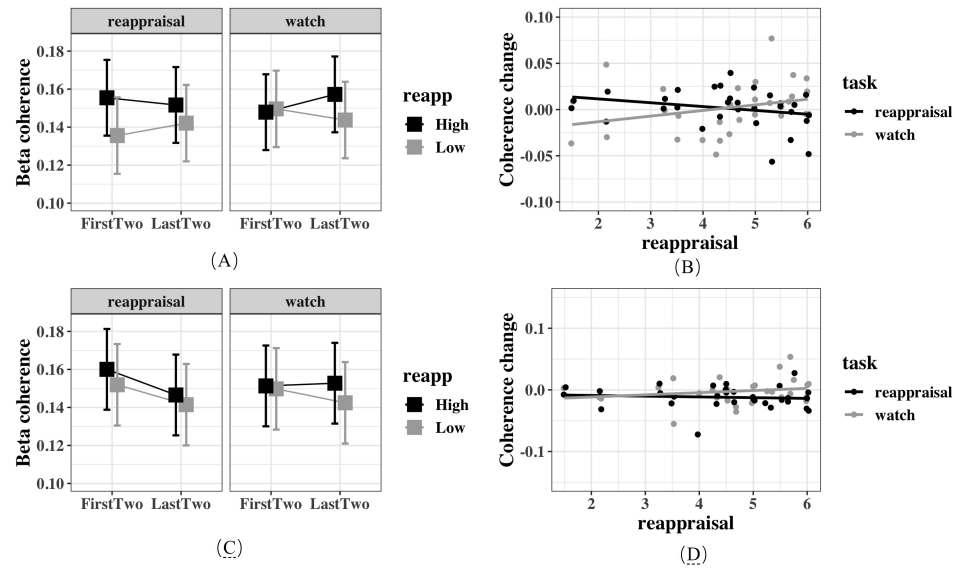


Figure 3.3: Three-way interaction plot of order task habitual reappraisal for the right-hemispheric prefrontal-posterior EEG beta coherence. (A) Neutral (FirstTwo) to Negative (LastTwo) and (C) Negative (FirstTwo) to Neutral (LastTwo). Scatter plots on the right show habitual reappraisal as a continuous variable in (B) and (D).

### 3.4 Discussion

A growing literature demonstrates that temporal dynamics of emotion are related to emotion regulation, with inflexible emotion regulation in response to event changes associated with psychopathology. In the current study, we examined patterns of neuropsychological changes to dynamic shifts in affective stimuli. We also included an experimental manipulation of emotion regulation strategy during the task and assessed individual differences in everyday reappraisal use. We modeled emotion transition as a person (habitual reappraisal) by situation (stimuli context change) and by strategy (passive watch vs. reappraisal) interaction. Our findings revealed that functional connectivity of cortical regions, specifically prefrontal-posterior EEG spectral coherence, changed

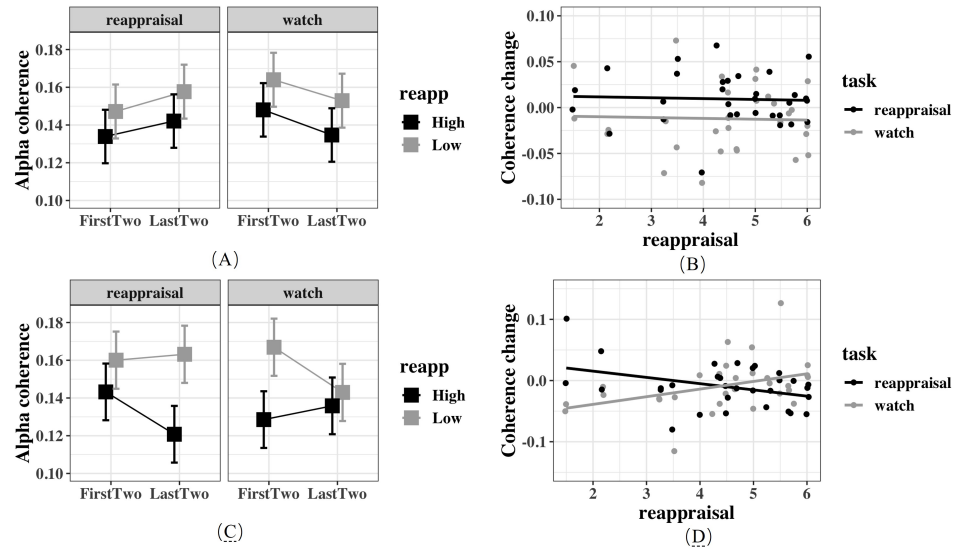


Figure 3.4: Three-way interaction plot of order task habitual reappraisal for the right-hemispheric prefrontal-posterior EEG alpha coherence. (A) Neutral (FirstTwo) to Negative (LastTwo) and (C) Negative (FirstTwo) to Neutral (LastTwo). Scatter plots on the right show habitual reappraisal as a continuous variable in (B) and (D).

along with affect stimulus changes and the use of cognitive reappraisal for people with greater habitual reappraisal style. As emotion regulation is jointly enacted through the affordances of the brain, body, and environment [21], it would be valuable to develop a family of models that can be applied to describe and explain the tremendous variability seen in instances of emotion regulation across different people, evocative situations, and regulatory strategies.

### *Habitual Reappraisal on Emotion Transitions in Beta Coherence*

According to previous evidence on changes in prefrontal-posterior coupling [24, 25, 26, 27, 28, 29, 30], beta coherence reflects individual differences in prefrontal control of aversive information. For example, individual differences in processing social-emotional stimulation are reflected with EEG coherence, as indicated by investigations of trait rumination and absorption [29]. The present findings on beta coherence are consistent with other studies which used beta coherence to examine emotional processing and overall control (Fig. 3). During the watch task, individuals with greater habitual reappraisal, beta coherence increased when images changed from neutral to negative, but beta coherence maintained when images changed from negative to neutral. This pattern reflected overall effective coping with demanding negative images and their residual influences. However, for individuals less reliant on cognitive reappraisal, their beta coherence tended to decrease regardless of image transitions. This indicates that with a series of images presentations and transitions, prefrontal control over parietal region loosened spontaneously for the subset of participants who typically do not utilize cognitive reappraisal when confronted by emotion transitions regardless of affect. During the reappraisal task, however, individuals with less habitual reappraisal use could alter beta coherence

according to external image affect type, with relative higher beta coherence corresponding to negative images; while individuals with greater habitual reappraisal use had beta coherence reduction or maintained. Our results also show that during voluntary reappraisal, individuals less reliant upon cognitive reappraisal could temporally increase control over aversive stimuli during emotion transitions.

### *Habitual Reappraisal on Emotion Transitions in Alpha Coherence*

It is notable that individuals who more typically use cognitive reappraisal more readily modified their right-hemispheric alpha coherence along with changes in affect (neutral compared to negative) (Fig. 3.4). Even though those with greater habitual reappraisal exhibited opposite coherence changes for the watch and reappraisal tasks, their coherence remained consistent with the type of affective content, and the sequential order of the two stimuli did not matter. However, for individuals with less habitual reappraisal style, alpha coherence decrements were consistently observed during the watch task; whereas coherence remained unchanged (or slightly increased) during the reappraisal task. Alpha coherence appears to reflect flexible transitions during both watch and reappraisal task conditions.

In our data, alpha coherence may reflect cognitive costs. Cognitive control has a general role in emotional regulation [44]. Higher intensity negative stimuli were associated with greater cognitive costs of reappraisal [45, 46]. However, greater habitual use of cognitive reappraisal, an individual difference factor, predicted lower cognitive costs of reappraisal [45]. Individuals with less habitual reappraisal manifested higher alpha coherence throughout image viewing. This could reflect greater consumption of cognitive capacity during emotion



transition and reappraisal task or that they had less cognitive capacity to start with.

### *Emotion Regulation and Emotion Transitions*

Our data provide the first empirical evidence that individual differences in emotion regulation can moderate the neurocognitive signature (EEG prefrontal-posterior alpha and beta coherence) induced by changes in emotional context. Individual differences in habitual reappraisal manifested in emotion transitions, and regulation tasks in the present study indicate that emotion transition might trigger spontaneous processes. Individual variability in emotion regulation has been shown both spontaneously and voluntarily (e.g., reappraisal) [18, 47, 48]. While voluntary regulation requires motivation, spontaneous emotion regulation appears to be stable and trait-related [49]. According to the strategy-situation fit theory of emotion regulation [50], people only use cognitive reappraisal when situations are perceived to be uncontrollable. However, because emotion regulation frequency is related to differentiation among emotions, individuals use more emotion regulation strategies when they can differentiate among a variety of negative and positive discrete emotions [51]. Once emotional affect intensity and/or valence changes, individuals perceive different levels of controllability, which would be associated with different neural responses. We have shown that individuals who had more everyday reappraisal use can more flexibly respond to shifting affective stimuli as indexed by alpha band coherence. One explanation for this could be because they better differentiate the change and flexibly allocate cognitive resources. We have also shown that individuals who had less everyday reappraisal use tended to reduce their alpha and beta band coherence regardless of affect stimuli type change during watch

task. This might reflect that they could not readily differentiate the different situations and execute necessary regulatory mechanisms, which resulted in inflexible neural responses.

Understanding the temporal dynamics of emotional processes may inform our understanding of cognitive capacity required to regulate emotional episodes [52]. Emotion dynamics not only reflect transient, momentary responses to a current stimulus but also are influenced by the previous context. Why might the context influence emotion transition? Emotional processing encompasses both reactivity and recovery, but neuroimaging studies to date have primarily focused on the magnitude of reactivity. In one of the only studies of recovery, amygdala activity immediately after emotional stimuli presentation (not the magnitude of reactivity in the amygdala during the task) was positively correlated with trait neuroticism [7]. If the previous stimulus terminates and is immediately followed by a new stimulus with different affective valence or intensity, the recovery from the previous stimulus response and reactivity to the new stimulus might interrelate. In this situation, the individual would need to process residual affect from the immediately previous emotional stimulation in conjunction with the current emotional stimulus (i.e., the emotion transition). The conflicting affect would likely require cognitive control in order to resolve the juxtaposition of the different emotional experiences [31].

Beta and alpha oscillations are generated by a common mechanism and modulated by additional mechanisms [53]. As suggested by Fig. 3.3 and Fig. 3.4, alpha and beta frequency band responses appear to work reciprocally for neutral  $\rightarrow$  negative and negative  $\rightarrow$  neutral conditions, though the results on beta coherence, unlike alpha coherence, did not reach statistical significance af-

ter Bonferroni correction of multiple comparisons. The coordinated yet complementary functions of alpha and beta coherence may help us draw a complete picture of neural activity during emotion transitions and regulation.

### ***Limitations and Future Directions***

Although we manipulated emotion regulation strategy using a previously validated protocol [35, 8], the validation procedures have been limited to EEG measurement and have not included other psychophysiological measurements, such as corrugator electromyography, or self-reported affect. Another potential limitation of the emotion regulation manipulation protocol we applied is the within-subject experimental design. The watch and reappraisal task conditions might contaminate each other, although we incorporated an inter-trial distraction task (flanker task) to minimize contamination. Though statistical analysis showed significant differences in both tasks, this might be related to individual differences in reappraisal use rather than the experimental manipulation of watch and reappraisal. Even though specific instructions were given for the reappraisal task along with practice and feedback from the experimenter, it is still possible that participants with different habitual reappraisal might unconsciously employ different reappraisal strategies when instructed on cognitive reappraisal. We instructed participants to cognitively reappraise the images; however, different forms of cognitive reappraisal strategies can involve different neural circuitries, which are differentially successful in different populations. Future studies would ideally investigate specific types of cognitive reappraisal, and their neural substrate changes during emotion transitions with functional neural imaging methods. Future study should also address the relationship between EEG alpha and beta frequency band with larger samples to ensure ad-

equate statistical power.

Whereas other research has focused on neural substrates of independent events evoking an emotional response, our study considered neural responses dependent on prior events. The design of the two images from the same affect type was deliberate because we wanted to study the affect transition rather than image transition. The dynamic stimuli could be a fast and sensitive probe to detect dysregulation. Our image sequence conditions with affect type transitions robustly engaged EEG coherence change and therefore should be an effective probe of the neural basis of emotional dynamics. The current study focused on transitions between neutral and negative images. In the future, additional affect transitions (e.g. negative to positive and the obverse) would be valuable in order to examine the generalizability of our results to emotion regulation embedded in variable, dynamic emotion transitions.

Summarizing, the long-term objective of our work is to understand the interrelations among emotional experience, environmental context, emotion regulation, and psychopathology, with particular attention to the neurodynamic of emotion transitions. Maladaptive emotion dynamics reflect rigid responses, which may be associated with dysregulation and psychological disorders. As an initial step in our program of research, we have tested in a non-psychiatric sample whether EEG coherence between the prefrontal and posterior cortical regions during dynamic, emotional experiences is associated with both experimental manipulations of emotion regulation strategies as well as individual differences in habitual use of the same strategy in daily life. The use of dynamic emotional stimuli in conjunction with EEG coherence as a biomarker both offer some new directions for exploration of underlying biomarkers indicative of

pathophysiological processes in psychiatric populations.

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CHAPTER 4

**INTERACTION OF SELF-REGULATION AND CONTEXTUAL EFFECTS  
ON PRE-ATTENTIVE AUDITORY PROCESSING: A COMBINED  
EEG/ECG STUDY**

*Abstract*

Environmental changes are not always within the focus of our attention, and sensitive reactions (i.e., quicker and stronger responses) can be essential for an organism's survival and adaptation. Here we report that neurophysiological responses to sound changes that are not in the focus of attention are related to both ambient acoustic contexts and regulation ability. We assessed electroencephalograph (EEG) mismatch negativity (MMN) latency and amplitude in response to sound changes in two contexts: ascending and descending pitch sequences while participants were instructed to attend to muted videos. Prolonged latency and increased amplitude of MMN at fronto-central region occurred in ascending pitch sequences relative to descending sequences. We also assessed how regulation related to the contextual effects on MMN. Reactions to changes in the ascending sequence were observed with the attention control (frontal EEG theta/beta ratio) indicating speed of reaction, and the autonomous regulation (heart-rate variability) indicating intensity of reaction. Moreover, sound changes in the ascending context were associated with more activation of anterior cingulate cortex and insula, suggesting arousal effects and regulation processes. These findings suggest that the relation between speed and intensity is not fixed and may be modified by contexts and self-regulation ability. Specifically, cortical and cardiovascular indicators of self-regulation may specify different aspects of response sensitivity in terms of speed and intensity.

## 4.1 Introduction

With the dynamic nature of the ambient environment, organisms as ensembles of both brain and body interact with the environment while maintaining equilibrium through adaptation and regulation [1, 2]. Although it is generally accepted that this adaptation results from the integration of brain, body and environment [2], the neural basis in this system is less well understood. One role that the brain plays is the modulation of perceptual sensitivity based on contextual information from the environment. For example, perception of a tone pitch was biased towards previously heard pitches, reflecting the temporal binding of successive frequency components [3]. Unattended changes in a regular context was associated with higher neural responses than in a random context, indicating that the brain is more sensitive to change in a predictable context [4]. This responsiveness to environmental changes is essential for survival, especially when changes are not always in the focus of attention. However, it remains unclear how the brain responds to changes in unattended stimuli in different dynamic environmental contexts and in what way the brain and body work together to regulate response sensitivity to such stimuli. Sensitivity to stimuli has usually been shown to be reflected in a quicker and stronger neural response. Thus, the purpose of this study is to examine how the perceptual sensitivity (i.e., speed and intensity) of the brain's responses to unattended changes modulated by the environmental contextual information and its association with regulation mechanisms from brain and body.

We study unattended sensory information processing by measuring neural responses to ambient acoustic stimuli, following the well-established electroencephalograph (EEG) based Mismatch Negativity (MMN). MMN is evoked by a

deviant event in a sequence of repeated or familiar events (the standards) when people are not focusing on the stimuli [5]. When immersed in ambient environmental stimuli, the brain predicts sensory inputs and compares the incoming stimuli with top-down predictions, eliciting an MMN when a prediction error is detected [6, 7]. Our experiment used ascending pitch sequences or descending pitch sequences as contexts. The primary aim was to assess the effect of context on the MMN response in terms of intensity (i.e., amplitude) and speed (i.e., latency, the timing from stimulus onset to response peak).

Prior work indicates that the pitch of environmental sounds alters perceived valence and arousal of auditory stimuli [8, 9, 10]. The stimuli were designed to have equal intensity, but the higher pitch stimuli would also be perceived as louder and the lower pitch as softer, as per loudness-frequency curves. The pitch and loudness are fundamental characteristics of speech that embody emotional context [11]. The regular pattern of the ambient sound context might generate an environmentally induced affective state which triggers self-regulation processes. Thus, we hypothesized that arousal and biological regulation mediate contextual effect on response to unattended changes. Usually, MMN latency and amplitude have been found to be related, with a quicker (smaller latency) and a larger (greater amplitude) MMN response indicative of sensitivity to change, both because of variations in deviant stimuli and cognitive decline [12, 13, 14, 15]. Therefore, the second aim was to understand MMN response intensity and speed in relation to arousal and regulation processes. Self-regulation involves volitional and nonvolitional components enabled by executive functioning and autonomous system [16, 17]. As a biomarker of executive functioning, EEG frontal theta/beta ratio reflects prefrontal cortex-mediated executive control over attentional and emotional information, with lower frontal



theta/beta ratio representing better focused attention and emotion regulation [18]. As a biomarker of autonomic regulation, heart rate variability (HRV) reflects stress and regulated emotional response, with higher values representing better regulation [19]. Therefore we apply these biomarkers to examine MMN responses in different contexts.

## 4.2 Methods

### *Participants*

Twenty right-handed students ( $M = 20.38y$ ,  $SD = 2.64$ ; 14 females) from Cornell University participated in this study. Exclusion criteria were the use of any medication that could affect nervous and cardiovascular systems and any history of neurological disorders. The study was approved by the Cornell University Institutional Review Board. Informed consent was obtained, and participants were compensated with either class credits or \$20.

### *Experiment*

Participants were individually immersed in auditory oddball streams that were either rapidly ascending in pitch (600 *Hz* - 1400 *Hz*) or descending in pitch (1400 *Hz* - 600 *Hz*), while they were asked to watch a self-selected silent documentary. The deviant in each stream was the last pitch, 1600 *Hz* instead of 1400 *Hz* in an ascending stream and 400 *Hz* instead of 600 *Hz* in a descending stream (Figure 4.1a). We did not compare the difference between low and high ends but addressing the low- and high-end changes with contexts of constantly changing auditory sequences. Therefore, the nonlinear auditory perception of

pitch on MMN will be tested in the future study.

A single sound stimulus was a five-tone cluster in ascending or descending sequence conditions. Each tone 50 *ms*, therefore a stimulus was 250 *ms*. The auditory paradigm involved the presentation of 1260 sound stimuli as a se-

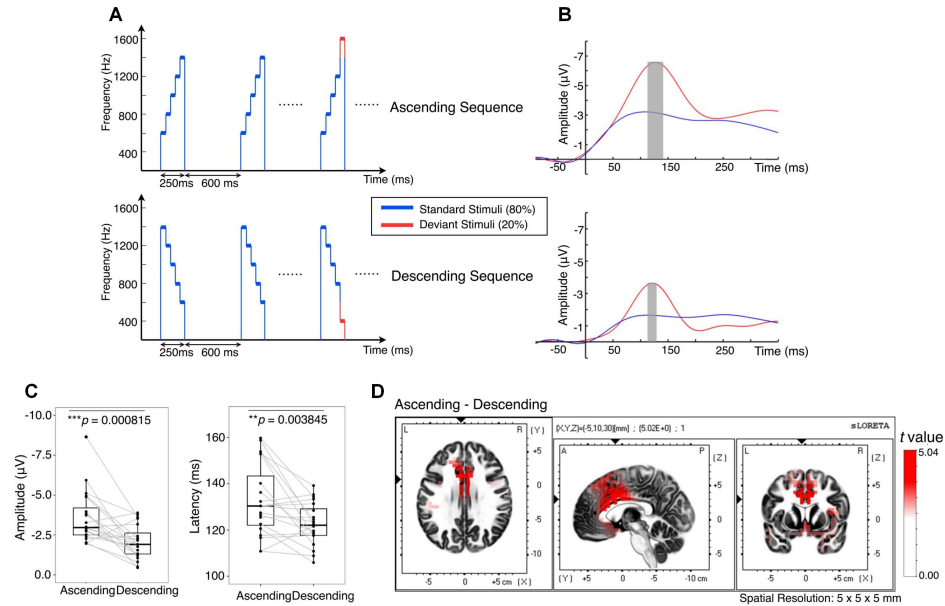


Figure 4.1: Contextual effect on brain responses to unattended sound changes. (a) Twenty percent of the stimuli set in either context had a deviant tone (plotted in red): a 200 *Hz* additional pitch increment or decrement tone in substitution to the fifth tone of the standard stimuli. (b) Grand average MMN at electrodes having the largest difference between standard and deviant in the fronto-central region. Grey bars are peak intervals (peak latency ± *SD*, *N* = 20) for ascending context at 118 *ms* - 149 *ms* and descending context at 114 *ms* - 132 *ms*. (c) MMN amplitude was greater in the ascending context ( $-3.60 \pm 1.65 \mu V$ ) than in the descending context ( $-2.08 \pm 1.06 \mu V$ ),  $t(19) = -3.97$ ,  $p = 0.0008$ . MMN latency was greater in the ascending context ( $132.84 \pm 15.53 \text{ ms}$ ) than in the descending context ( $122.55 \pm 9.15 \text{ ms}$ ),  $t(19) = 3.29$ ,  $p = 0.0038$ . (d) Significant increase (when  $t > 2.093$  for corresponding voxel) in current source density of the MMN in the ascending condition compared with the descending condition at the respective peak intervals.

quence of ‘standard’ stimuli (80%) randomly interspersed by ‘deviant’ stimuli (20%). Each type of context (ascending and descending) was divided into 7 runs with each consisted of 144 standards and 36 deviants maintaining the 80/20 ratio. The first 10 stimuli in each run were specifically standards (to establish the expectation), followed by a pseudo-random distribution of standards and deviants, avoiding consecutive deviants. The runs of the two sequence contexts were randomly presented. EEG was recorded using 128-channel BioSemi system at a sampling rate of 512 Hz. ECG was recorded from three BioSemi electrodes placed on left and right abdominal region and the region below the right collarbone. Stimuli were presented via BCI2000 software at 55 *dB*A via speakers placed 40 *cm* in front of the participant. The sound pressure level was measured with a sound meter at the location of subject’s head.

### *Analysis*

EEG was re-referenced to the algebraic average of left and right mastoids, and was bandpass filtered between 0.1 and 55 Hz. For event related potential (ERP) analysis, the signal was further filtered between 0.5 and 10 Hz (for different filtering comparison see Figure 4.3). Bad channels were identified and spherically interpolated. Data was epoched into -100 to 350 *ms* trials, where time 0 was defined as the time of stimulus onset asynchrony which was 200 *ms* after the start of the complex tone pattern, which was also the start of the last tone. The artifacts due to eye movements, muscle and cardiac activity were removed with Independent Component Analysis, using the EEGLab toolbox [20]. The epochs were averaged across trials for each channel to obtain the evoked response. The [-100 0] *ms* period before the last tone was used for baseline correction. All the standard stimuli were averaged, and also the deviant stimuli, and

then the MMN waveform was calculated as the difference between ERP of the deviant stimuli and the standard stimuli. For the MMN waveform with baseline correction during the trial interval [-300 -200] ms, see Figure 4.4. We used the coefficient-of-determination ( $r^2$ ) to quantify the difference between standard and deviant responses in each time point after the stimulus. The  $r^2$  was calculated as the square of the Pearson correlation coefficient between the amplitude in each time point and the trial label (standard or deviant). Then we individually selected the fronto-central channel that has the negative peak with largest  $r^2$  within 80-200 ms [6].

Current source densities in each voxel between two conditions (ascending vs descending) were compared by randomization tests on paired data (5000 permutations). Based on statistical non-parametric mapping (SnPM; for details see [21]) corrected for multiple comparison, we used the sLORETA [22] software to perform “non-parametric randomization” of the data. Besides, we estimated the ratio of the theta (4-7 Hz) and beta (14-30 Hz) power at the frontal regions [18], including C21, C32 and C10 channels. In terms of the HRV analysis, we used the Pan-Tompkin algorithm to extract the QRS complex and detect the peak of the R waveform, and then measured the R-R interval between successive R-to-R peak. Then we used the root mean square of the successive differences (RMSSD) of the R-R interval to quantify the HRV [23]. These variables were calculated for each participant under each sequence context across runs. We explored the non-linear relationship between these biomarkers using the Spearman correlation test.

Paired  $t$ -test was used to examine the MMN amplitude and latency between ascending and descending context. Linear mixed effect models were used to

investigate the interaction of self-regulation biomarkers and contexts on MMN amplitude and latency respectively. High and low theta/beta ratio and HRV were plotted  $\pm 1$  SD from the mean in the Figures.

### 4.3 Results

MMN was obtained by subtracting the response to the standard stimulus (blue) from the response to the deviant stimulus (red) (Figure 4.1b). The ascending context elicited a slower ( $p < .01$ ) but larger ( $p < .001$ ) MMN than the descending context (Figure 4.1c). Furthermore, current source density of MMN in the ascending context was significantly higher than descending context in the in-

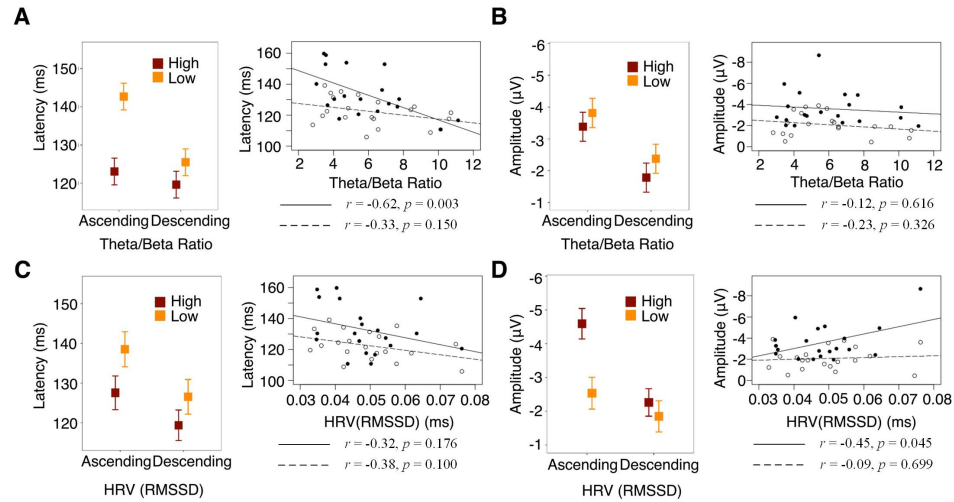


Figure 4.2: Contextual effect modulated by regulation biomarkers. (a) Statistical interaction modeling showed that theta/beta ratio interacted with context on MMN latency,  $\chi^2(1) = 5.10, p = 0.0239$ . (b) Theta/beta ratio did not interact with context on MMN amplitude,  $\chi^2(1) = 0.04, p = 0.8448$ . (c) HRV did not interact with context on MMN latency,  $\chi^2(1) = 0.24, p = 0.6234$ . (d) HRV marginally interacted with context on MMN amplitude,  $\chi^2(1) = 3.67, p = 0.0555$ .

sula,  $p < .01$ , and in the cingulate gyrus including anterior cingulate cortex (ACC),  $p < .001$  (Figure 4.1d). Moreover, the source density of MMN filtered within broad-band [0.5 55] Hz showed a similar result (Figure 4.5). These results are consistent with the error detection mechanism mentioned above as the anterior cingulate cortex contributes to attention, which serves to regulate both cognitive and emotional processing [24]. On the other hand, the insula receives viscerosensory inputs and responsible for affective experience, particularly in negative emotion suppression [25, 26]. Altogether, the results indicate that the brain is more sensitive to changes in the ascending context and executed more regulation procedures.

We then examined how MMN amplitude and latency were associated with regulation biomarkers. A nonlinear correlation (Spearman correlation test) existed between theta/beta ratio and HRV ( $p < .01$ ): moderate theta/beta ratio corresponded to the highest HRV and, as theta/beta ratio increased, HRV declined. We found that both theta/beta ratio and HRV were not significantly different between ascending and descending context (Figure 4.6). However, higher theta/beta ratio was associated with smaller MMN latency and higher HRV was associated with larger MMN amplitude in the ascending context, whereas no correlations were found in the descending context (Figure 4.2a-d).

## 4.4 Discussion

Sensitivity to stimuli means a quicker and/or stronger neural response. Interestingly, in our study, the ascending auditory context induced stronger yet slower neural responses, i.e., a larger but later MMN. This phenomenon is

different from previous findings wherein the latency and the amplitude of MMN were negatively correlated that together reflect the sensitivity to change [12, 13, 14, 15]. If deviants in ascending were simply more salient than in descending, they would be expected to elicit greater amplitude and smaller (or similar) latency. Thus, these data suggest 1) reaction intensity and speed may reflect different aspects of sensitivity, which were possibly processed by different mechanisms, and 2) when exposed to different contexts, these mechanisms could be differentiated. Moreover, the MMN latency and amplitude did not correlate with each other in any context or cross contexts (Figure 4.7), further supporting that deviant stimuli with higher pitch not only influence sensitivity but are also associated with the interaction of regulation and context. Regulation biomarkers can account for neural responses to unattended changes, but only under some specific conditions, such as the ascending pitch context described in this study. Further, the response intensity and speed can be accounted for by cortical and cardiovascular biomarkers of regulation respectively.

The anterior cingulate and insula are involved in the central autonomic neural network, which is a part of an internal regulation system wherein the brain controls visceromotor and neuroendocrine processes, essential for adapting to environmental demands [27]. As during the ascending context, more activation in ACC and insula was observed, the context-related heightened arousal might trigger more regulation, so that participants could adapt. Participants with higher HRV throughout the experimental sessions elicited stronger MMN, reflecting better regulation during unexpected changes.

Attention has been shown to influence MMN generation [28, 29]. In our study, though participants were instructed to focus their attention on docu-

mentary videos, their neural responses to deviant stimuli differed because individual attentional control as one of the regulation processes was manifested. Slower response was observed in individuals with low theta/beta ratio. These individuals were superior in attentional control during focused attention tasks [18, 30] and might allocate more regulation effort to the elevated arousal experienced during the ascending sound context. The low theta/beta ratio individual would be less sensitive to unattended stimuli changes. However, participants who were inferior in attentional control might be more susceptible to distraction, especially for those having higher theta/beta ratio in individuals diagnosed with ADHD or anxiety disorders [31, 30]. In unattended situations, they might be more sensitive to changes in terms of response speed. They might also show attenuated neural response, due to the nonlinear relation between theta/beta ratio and HRV.

Summarizing, sensory stimuli do not reflect the simple pattern of immediate energy; rather they contain focal, contextual and organic components (regulation) [2]. The pooled effect of these components determines and maintains a neural trace of the contextual effect, where the focal component of a deviant stimulus impinges upon organisms already adapted to the context [2, 32, 3]. With different ambient auditory contexts, our data showed the dissociation of the presumed negative correlation between amplitude and latency of the MMN response. Perhaps contexts influence MMN on both physiological and psychological aspects. Latency of the MMN changes depends on the time when the deviance in stimulus is detected, thus to the threshold of the sensory system for the change, which is rather physiological and thus objective. The amplitude of the MMN, on the other hand, changes depending on the salience of the deviance for the subject, which is rather psychological and thus subjective. Therefore, as-



sessing perception and adaptation to ambient environmental changes requires a more holistic perspective including context along with regulation capacities.

## Supplementary Figures

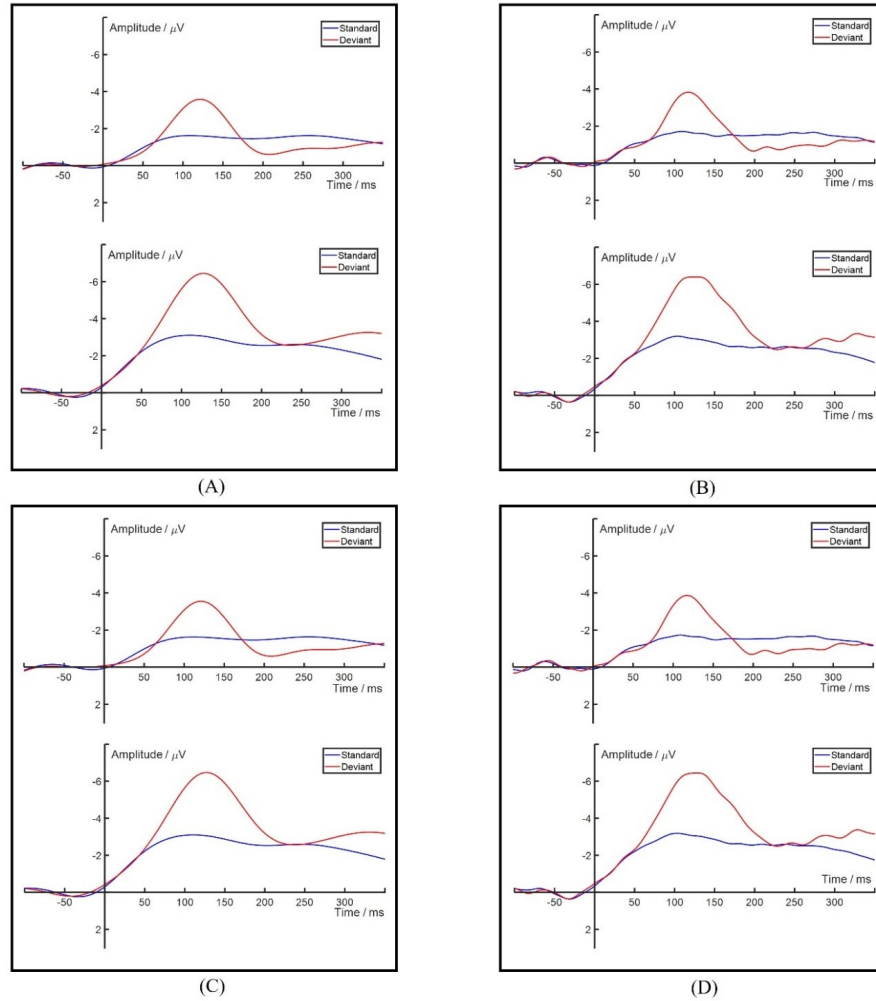


Figure 4.3: The influence of the filtering parameters on the ERP waveforms with respect to the descending and the ascending sequence. (A) The EEG signal was filtered within 0.5 and 10 Hz, with the upper one corresponding to the descending sequence and the lower one corresponding to the ascending sequence. (B) The EEG signal was filtered within 0.5 and 40 Hz. (C) The EEG signal was filtered within 0.1 and 10 Hz. (D) The EEG signal was filtered within 0.1 and 40 Hz.

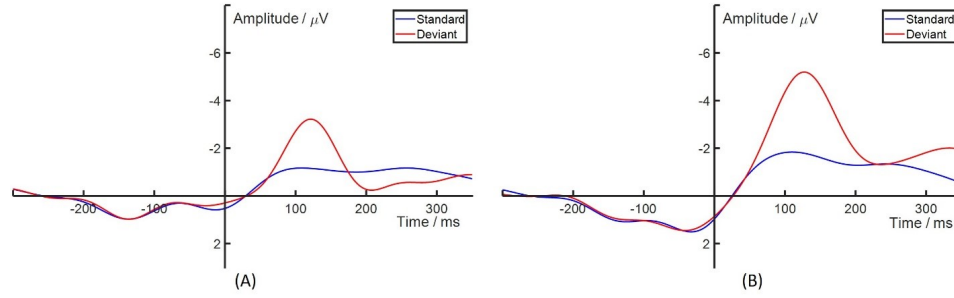


Figure 4.4: The ERP with respect to descending sequence in (A) and ascending sequence in (B). The baseline was within [-300 -200] ms, during which period no stimulus was presented.

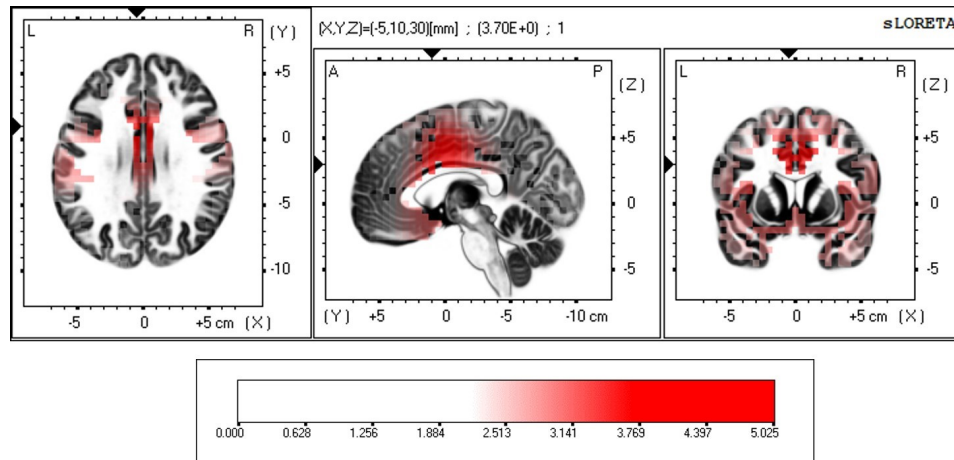


Figure 4.5: Statistics (t value) of the current source density of the MMNs (0.5~55 Hz) in the ascending condition compared with the descending condition.

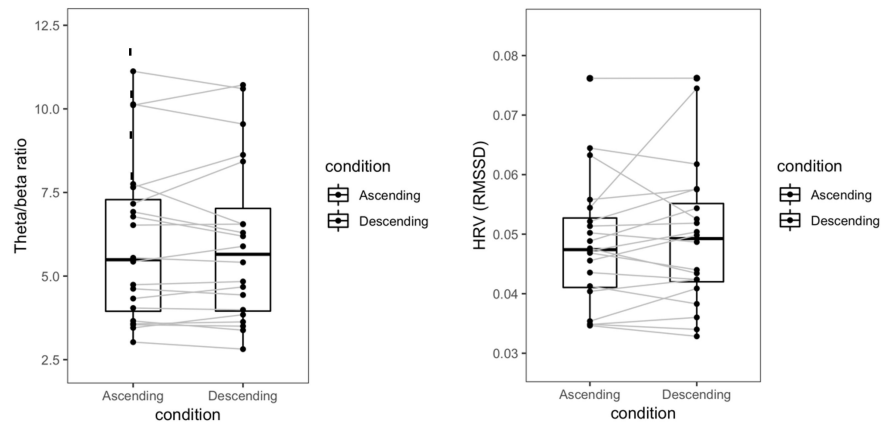


Figure 4.6: Theta/beta ratio and HRV in two conditions. Paired t-test, theta/beta ratio:  $t(19) = -0.77$ ,  $p = 0.4485$ , RMSSD:  $t(19) = 0.08$ ,  $p = 0.9360$

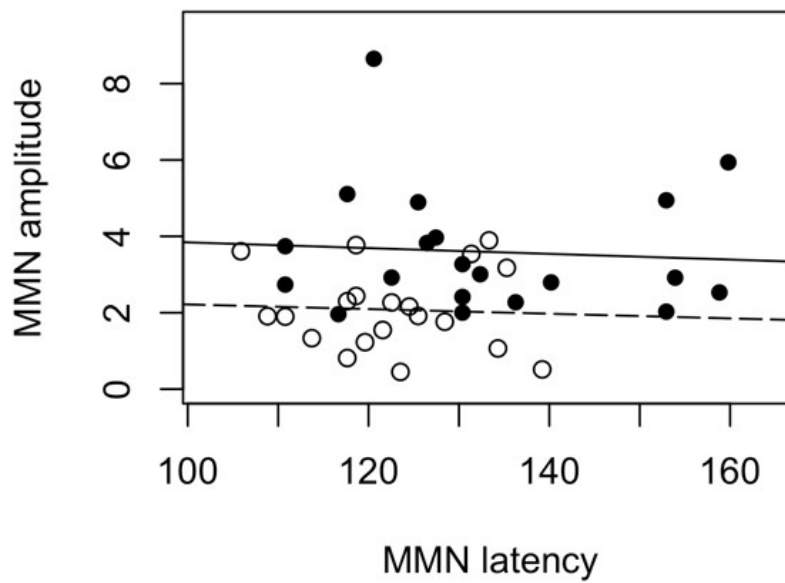


Figure 4.7: Correlation between MMN latency and amplitude. Across conditions,  $r = 0.14$ ,  $t(38) = 0.83$ ,  $p = 0.4097$ . In the ascending condition,  $r = -0.07$ ,  $t(18) = -0.30$ ,  $p = 0.7664$ ; in the descending condition,  $r = -0.05$ ,  $t(18) = -0.22$ ,  $p = 0.8259$ .

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## CHAPTER 5

### THE EFFECT OF DYNAMIC NATURE SUNLIGHT ON ACUTE STRESS RECOVERY

Environmental psychology has provided evidence for the effects of exposure to natural settings and lighting on cognition and emotion. Few studies, however, have assessed the neural correlates of these benefits nor have most studies examined brief exposures. The precise connection between changes in sunlight and concurrent individual experience and physiological activity are unknown. The present study used electroencephalography (EEG) to explore how the brain processes dynamic (increasing or decreasing brightness perception) vs. static (constant bright and dark) short-term (30s) sunlight during acute stress induced by a standard laboratory stressor (mental arithmetic). A blank screen was used as a baseline control. Participants ( $n = 31$  college students) rated their subjective relaxation state immediately after the acute stressor exposure. EEG beta frequency band power and subjective ratings were analyzed. Increasing sunlight was rated as more relaxing compared to other conditions. Beta power was the lowest during increasing sunlight condition, suggesting minimal cognitive and emotional demand compared to other lighting conditions. Furthermore, beta power in the parietal region statistically mediated the effects of natural lighting condition on subjective stress ratings during recovery. Visual perception of dynamic sunlight environments may require more involuntary attention and less directed attention compared with static lighting. This effect is manifested in brain activity characteristic of enhanced stress recovery. Dynamic lighting in short-term exposures may be capable of inducing self-regulation processes, which potentially could yield long-term cognitive and physical health benefits.

## 5.1 Introduction

As stressors, physical (noise, chemical, cold, etc.) or psychological experiences (unexpected events, social pressure, etc.) elicit stress responses, which can momentarily change heart rate, blood pressure, saliva cortisol, perspiration, etc. After exposure to a stressor, the body recovers from the stress. The metaphor of physical exertion is useful in thinking about physiological reactivity and recovery to a stressor. A fit, well-trained body can rapidly mobilize the cardiovascular system to engage in vigorous exercise and then when exertion ceases, quickly return to resting, baseline levels. Stress recovery is particularly crucial in psychological and physiological health. Stress recovery is related to self-regulation and influences affective states [1, 2]. Slower recovery to acute stressors has been found in individuals with chronic stress [3, 4]. Incomplete recovery may lead to chronic health impairment [5, 6]. As we spend most of our lifetime indoors, in places like our homes or workplaces, interventions for facilitating stress recovery when indoors could be valuable for well-being.

One of the indoor physical elements that influence psychological and physiological health is lighting. Lighting influences circadian rhythms. Natural sunlight is dynamic. For example, everyone recognizes short-term increased light at sunrise implying waking up and decreased brightness like sunsets reminding them to take rest. Lighting effects are different with dynamic changes in illuminance. Illuminance is given as the luminous flux per square meter (measured in lux) and is correlated to the perception of brightness. Brightness can affect cognitive performance and self-control. Bright light makes people feel more vital with enhanced self-regulation [7, 8] and dark light elicits relaxation [9], fewer constraints and more self-construal [10, 11]. When brightness can be

systematically changed, it is more beneficial than static lighting [12]. For example, dynamic lighting reduces pupils' restlessness and improves their social behavior in school [13] or facilitates stress recovery in hospitals [14]. These studies all relied upon relatively long durations of lighting exposure. If we want to intervene with lighting for acute stress recovery, short-term dynamic lighting seems like a suitable approach.

The present study investigates if short-term, dynamic natural sunlight is more effective for stress recovery than static lighting (constant bright or dark), promoting relaxation and changes in physiological responses. We embedded dynamic lighting in nature to make it more vivid and realistic in a laboratory setting. Moreover, natural environments have restorative effects, reducing physiological stress, facilitating executive functioning, and improving mood [15, 16, 17]. Usually, studies with nature exposure last several minutes to hours to test its restorative effect. Herein I examine whether short term (less than a minute) nature animation of sunlight can facilitate acute stress recovery, particularly under dynamic lighting conditions. A mental arithmetic task is employed to induce acute stress. This stress induction protocol is routinely used in autonomic function testing and commonly provoke changes in cardiac function indicative of increased sympathetic arousal [18].

The brain plays an important role in coordinating cardiovascular, immune, and other systems via neural and endocrine mechanisms during stress [19]. For instance, right prefrontal cortex activity has a role in cerebral regulation of heart rate by virtue of decreasing parasympathetic effects or increasing sympathetic effects [18]. Electroencephalography (EEG) reliably reflects acute stress level [20, 21], reflected by beta band power increases [22]. There is also evidence that

natural scenes decrease EEG alpha and beta waves compared with urban ones [23]. Specifically, we tested beta band power, as beta-band activity has been associated to cognitive and emotional processing [24]. Although EEG is limited with insufficient spatial resolution to infer neuroanatomical generators of its surface potentials, it has higher temporal resolution than techniques such as functional magnetic resonance imaging. EEG provides a suitable tool for detecting and characterizing specific phenomena in time and frequency domains. The emotional effects of stress involve feelings of anxiety, fear, distress, and other emotions, so we use a subjective rating of relaxation to index it. We also hypothesized that the subjective feeling of relaxing during stress recovery would be mediated by brain activity during dynamic lighting, nature animation.

## 5.2 Methods

### *Participants*

Participants were 33 psychologically healthy and right-handed college students. They had a normal or corrected-to-normal vision. Two participants were dropped because of recording problems yielding 31 (mean age = 23, SD = 2.5, 15 females). Participants were requested to refrain from alcohol, caffeine, and other stimulants for four hours before the experiment. They were also asked to sleep for at least six hours the night before the experiment. Participation was compensated with course credit or \$20. Cornell's Institutional Review Board approved the study. Informed consent was obtained from all participants.

### *Study Procedure*

Participants were comfortably seated facing the monitor at about 50 cm and followed the instruction on the screen. In each trial as shown in 5.1, participants first did a mental arithmetic task for 60 seconds before watching a nature animation for 30 seconds. Four different kinds of nature animation conditions were randomly presented in each trial: constant **bright**, constant **dark**, bright change to dark (**decrease**), and dark change to bright (**increase**). In the dynamic change conditions, sunlight gradually changed linearly in luminance. A blank screen condition was also included as a baseline. One trial of these five conditions presented randomly in a block. Four blocks in total, which means each condition had four trials across the experiment. After each block participants rested for 1 minute and did one minute of flanker task, which is not analyzed in this paper. At the beginning of the experiment, 3 minutes of resting state data were collected to assess participants' baseline.

For the mental arithmetic task, a 3-digit number (e.g., 897) showed on the center of the screen, and a 2-digit number (e.g., 13, 17 or 23) showed on the corner. Participants were instructed to subtract the small number from the big number and keep subtracting from the remaining value aloud. They were encouraged to do as many as possible in one minute. Participants stopped calculation once the screen changed to animation or a blank screen. They were asked to watch the screen during these periods. After 30 seconds, one question appeared on the screen asking participants to rate their momentary feeling ("how relaxed are you feeling now?") on a Likert scale from not at all (1), a little (2), rather (3) to very much (4). At the beginning of the experiment, 3 minutes of resting-state data were collected to assess participants' baseline. After the experiment, we briefly interviewed participants which recovery condition (including the blank screen) they liked the most.

## Measurement

EEG and skin conductance were measured simultaneously during the experiments. Scalp potential was recorded by EEG using 128-channel BioSemi system at a sampling rate of 512 Hz. EEG was re-referenced to the algebraic average of left and right mastoids and was bandpass filtered between 0.1 and 55 Hz. Bad channels were identified and spherically interpolated. Data was epoched into [0 30] s trials, where time 0 was defined as the time of animation (and blank screen) onset. Those signal segments with obvious abnormal signal segments were excluded for Independent Component Analysis (ICA). The artifacts due to eye movements, muscle and cardiac activity were removed with ICA, using the EEGLab toolbox [25]. After removing the artifact components, the ICA source signals were transferred back to the original signal space, which was then used for the subsequent analysis.

Preprocessed EEG signal was continuously segmented into 1s epoch with 0.1 s step size. In each epoch, a Hanning window was applied before calculating

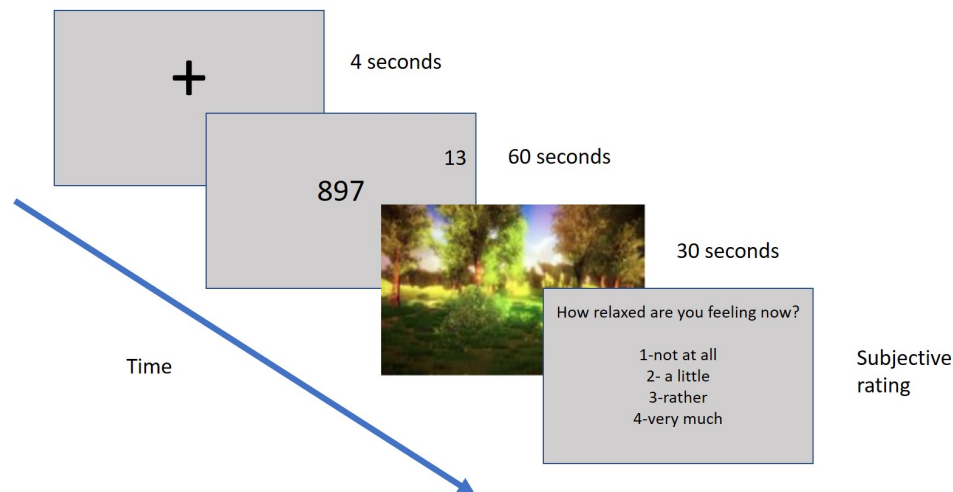


Figure 5.1: Experimental procedure: a complete trial.

the beta band power using Fast Fourier Transform. Within a trial, the epoch which was more than three scaled median absolute deviations away from the median was considered as an outlier and was removed for calculating the mean beta power within a trial. EEG beta power was averaged across trials in each stress recovery condition. We selected four regions for beta power evaluation in the statistical models: frontal left, frontal right, parietal left, and parietal right.

Continuous decomposition analysis was performed to decompose skin-conductance data into continuous tonic and phasic activity, by using Ledalab software of Version 3.3.1 [26]. The averaged phasic activity was calculated during each stress reduction phases and stress recovery condition.

### *Statistical Analysis*

First, we used skin conductance to validate the stress induction process, by modeling resting state, mental arithmetic phase, and blank relaxation phase (baseline recovery) in a mixed effects model. A separate model was conducted with EEG beta band power in each region. For relaxation ratings and EEG band powers, mixed models were applied with recovery conditions (four nature lighting conditions and blank screen) as a fixed factor, and each individual as a random effect. To examine each condition, post-hoc comparisons was conducted with Tukey method critical value correction.

Then, a mixed effect mediation model was applied to examine if EEG band power mediated subjective relaxation ratings during stress recovery. The blank screen condition was treated as a reference, and each of the other nature lighting conditions coded as dummy variables. The datasets generated during and/or analyzed during the current study are available from the corresponding author



on reasonable request.

### 5.3 Results

#### *Validation of stress induction and short-term stress recovery*

Different phases in stress induction had a main effect on skin conductance,  $F(2, 60) = 16.049$ ,  $p < 0.0001$  (Figure 5.2 A). Post-hoc pairwise comparison indicated stress reactivity induced by mental arithmetic task significantly elevated skin conductance compared to resting state reactivity ( $p < .0001$ ) and stress recovery during a blank screen significantly reduced skin conductance ( $p = .0238$ ). Thus, the mental arithmetic task successfully induced acute stress, and 30 seconds of relaxation was necessary.

I examined beta frequency band power [14 30] Hz on the frontal and parietal regions in both hemispheres, with significant effects of condition on beta power observed in all regions. Because beta power in the parietal region mediated the subjective rating of relaxation, we only report statistical results from parietal beta power. Different phases in stress induction had a main effect on EEG beta band power,  $F(2, 60) = 10.719$ ,  $p = .0001$  (Figure 5.2 B). Post-hoc pairwise comparison indicated stress reactivity induced by mental arithmetic task significantly elevated beta band power relative to resting state reactivity ( $p = .0001$ ). This suggests beta band power adequately represents task demand.

However, beta band power in recovery and reactivity phases were not significantly different ( $p = .395$ ). Beta band power was significantly higher in recovery phase than resting ( $p = .0063$ ) and skin conductance during recovery was higher

than resting ( $p = .0121$ ). These results suggest the blank screen recovery phase was not sufficiently long enough for participants to fully recover from stress physiologically.

### *Dynamic nature lighting effect on stress recovery*

Stress recovery conditions had a significant main effect on subjective rating of relaxation,  $F(4, 120) = 9.49$ ,  $p < .001$ , proportion change of variance (PCV) = 21.52% (Figure 5.3 A). Post-hoc pairwise comparison indicated that participants rated greater relaxation in every nature lighting condition compared with the blank screen, bright-blank,  $p = .0034$ , dark-blank,  $p = .0034$ , decrease-blank,  $p = .0098$ , increase-blank,  $p < .0001$ . Comparing among the four nature lighting conditions, dynamic-increase condition tended to be rated higher relaxation, increase - decrease,  $p = .0506$ , increase - bright,  $p = .111$ , increase - dark,  $p = .111$ . Subjective rating of relaxation was not related to preference. Though 12 people liked the dynamic-increase condition, only 6 of them rated dynamic

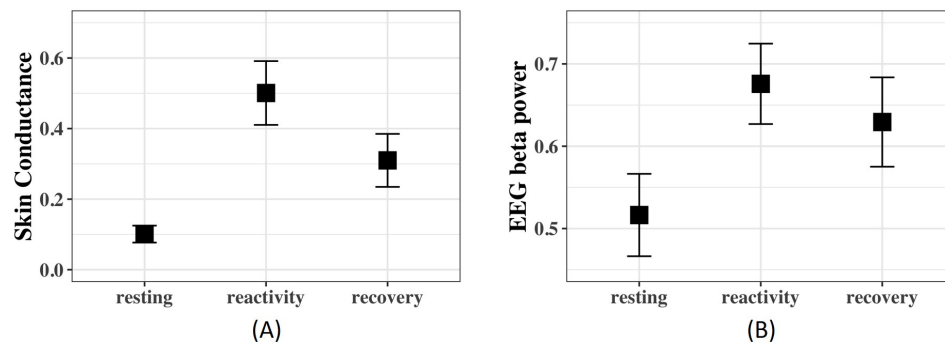


Figure 5.2: (A) Skin conductance responses during resting, mental arithmetic (stress reactivity), and blank screen condition (stress recovery). Mean changes in EDA ( $\mu S$ ) as a function of the stress induction phase. (B) Mean changes in EEG beta frequency band power ( $V^2/Hz$ ) at the parietal region as a function of the stress induction phase. Error bars represent standard errors..

increased condition as the most relaxing condition.

I found a significant main effect of condition on skin conductance:  $F(4, 120) = 2.478$ ,  $p = .048$ ,  $PCV = 4.55\%$  (Figure 5.3 B). Post-hoc pairwise comparison indicated that the dynamic-increase condition significantly reduced skin conductance relative to the blank screen,  $p = .051$ . The constant bright condition also emerged marginally significant, bright-blank,  $p = 0.067$ .

EEG beta frequency band power manifested significant difference across

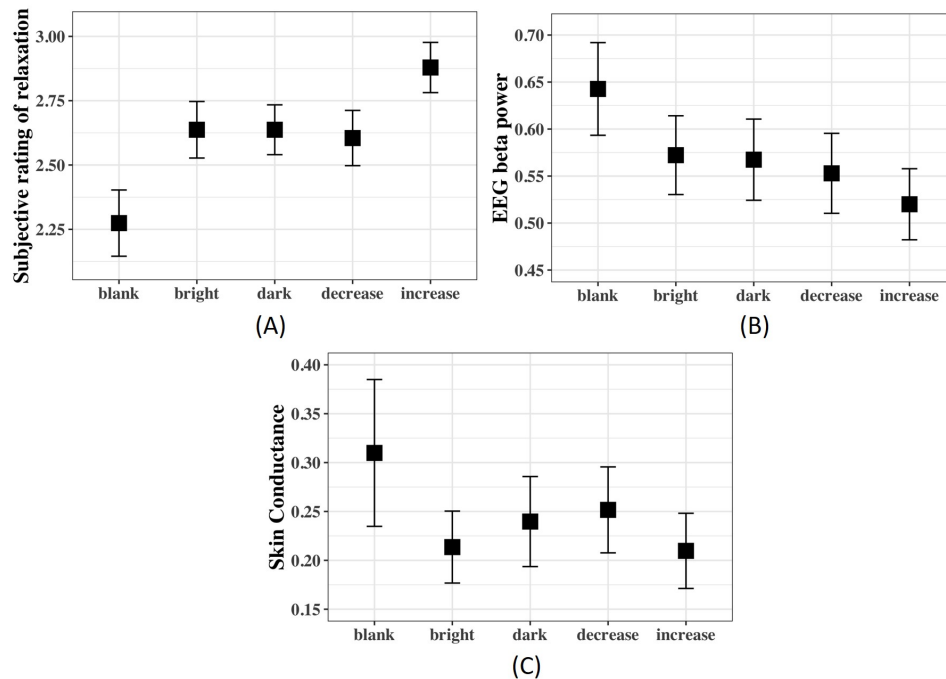


Figure 5.3: (A) Relaxation state ratings as a function of recovery conditions. After each stress recovery phase subjects rated their current state of “relaxation” each on a scale from 1 (not at all) to 4 (very much). (B) Mean changes in EEG beta frequency band power ( $V^2/Hz$ ) at the parietal region as a function of recovery condition. (C) Skin conductance responses during stress recovery. Mean changes in EDA ( $\mu S$ ) as a function of recovery conditions. Error bars represent standard errors.

Table 5.1: Estimates (standard errors) of subjective and objective stress recovery effect during each condition.

	Condition				
	blank	bright	dark	decrease	increase
Subjective rating	2.274 ( $\pm 0.129$ )	2.637 ( $\pm 0.109$ )	2.637 ( $\pm 0.097$ )	2.605 ( $\pm 0.107$ )	2.879 ( $\pm 0.098$ )
95% CI	[2.011, 2.537]	[2.413, 2.862]	[2.439, 2.835]	[2.386, 2.824]	[2.680, 3.078]
Skin conductance	0.310 ( $\pm 0.418$ )	0.214 ( $\pm 0.205$ )	0.240 ( $\pm 0.256$ )	0.252 ( $\pm 0.245$ )	0.210 ( $\pm 0.214$ )
95% CI	[0.156, 0.463]	[0.138, 0.289]	[0.146, 0.334]	[0.162, 0.341]	[0.131, 0.288]
EEG beta power	0.643 ( $\pm 0.274$ )	0.572 ( $\pm 0.233$ )	0.567 ( $\pm 0.240$ )	0.553 ( $\pm 0.237$ )	0.520 ( $\pm 0.211$ )
95% CI	[0.542, 0.743]	[0.487, 0.658]	[0.479, 0.656]	[0.466, 0.640]	[0.443, 0.597]

conditions,  $F(4, 120) = 13.121$ ,  $p < .001$ ,  $PCV = 28.11\%$  (Figure 5.3 C). Post-hoc pairwise comparison indicated that beta power was significantly reduced in every nature lighting condition compared with the blank screen condition: bright-blank,  $p = .001$ , dark-blank,  $p = .0003$ , decrease-blank,  $p < .0001$ , increase-blank,  $p < .0001$ . Comparing among the four nature lighting conditions, dynamic - increase condition induced lower beta power than static conditions, increase - bright,  $p = .0285$ , increase - dark,  $p = .0595$ .

The above results indicate that short-term dynamic-increase nature lighting condition is more effective in stress recovery than static nature lighting, promoting relaxation, and changes in physiological responses. Statistics of mean (SE) and 95% confidence interval are summarized in Table 5.1.

### *Brain activity mediates nature effects on relaxation*

Brain activity of EEG beta power predicted the subjective rating of relaxation across conditions,  $F(1, 73.097) = 8.415$ ,  $p < .0049$ , explaining 10.07% of the variance. We conducted a mixed effect mediation model to test if EEG beta power mediated the stress recovery condition on subjective relaxation. When the blank

Table 5.2: Statistics of mediation effect of beta power on subjective relaxation (blank screen as reference).

	Condition			
	bright	dark	decrease	increase
Coefficients (SE)	0.060 ( $\pm 0.026$ )	0.065 ( $\pm 0.027$ )	.077 ( $\pm 0.031$ )	0.105 ( $\pm 0.039$ )
95% CI	[0.008, 0.111]	[0.012, 0.118]	[0.017, 0.137]	[0.027, 0.183]
p-value	0.019	0.017	0.012	0.008

screen was treated as a reference, the indirect path test statistics of each nature lighting condition is summarized in Table 5.2. The results indicate that EEG beta power mediated the effect of nature lighting conditions on the subjective rating of relaxation.

## 5.4 Discussion

Settings with natural elements effectively influence stress and emotional feelings, as well as bring cognitive and social benefits. I examined if short-term, dynamic lighting embedded in natural sunlight animation could make people feel more relaxed than constant static bright light or dark light after acute stress. I also sought to understand the underlying neural mechanisms to explain why dynamic lighting might have different effects on stress recovery in comparison to static lighting. Self-reports showed that 30 seconds animation of nature sunlight was rated as more "relaxing" compared to the blank screen after acute stress, in line with previous research. Among the natural sunlight animation conditions, the one with gradually increasing sunlight (dynamic-increase condition) was rated as the most relaxing. Physiologically, skin conductance revealed

that dynamic-increase condition significantly reduced sympathetic activation compared with blank screen condition. EEG beta wave power over frontal and parietal electrodes on both hemispheres was reduced more during nature animation than the purely blank screen, as expected. Moreover, the dynamic-increase condition, again induced the lowest beta power compared with the static conditions. Thus, self-report, EEG beta wave power, and skin conductance all converge in showing that dynamic increases in simulated sunlight may have salugenic qualities.

In this experiment, lighting is the only difference in the four nature animation conditions. Previous research demonstrated that lighting brightness can influence self-regulation [27, 8]. Though bright light reduces negative emotions and enhances inhibition without conscious self-control efforts in relatively long exposures, acute dynamic lighting effect on self-regulation might function differently. Increasing or decreasing brightness perception might elicit participants' bottom-up attention, which is typically driven by stimuli rather than volitional control. During dynamic stimulation, the coupling between the frontal and posterior regions of the brain is weakened [28]. The frontal control over the posterior region is reduced, indicating that the brain is more susceptible to direct environmental stimulation. Prior work has shown that dynamic stimuli with varying negative intensity have a larger impact on people's executive functioning than static intensity stimuli [29, 30]. Additional cognitive effort might be required to process dynamic shifts in stimuli, especially when they are unpredictable or have negative valence. As an extreme example, people may feel shocked when a glaring light appears in the dark or sudden outage for a few seconds, compared with constant bright light or dark environment. However, in the present study, the dynamic lighting changed predictably either with in-

crease or decrease brightness perception. Dynamic lighting embedded with a nature scene could additionally enhanced stress reduction because of attention restoration.

Natural environments restore human's ability to focus on a specific task while effortlessly inhibiting distractors [31, 32]. Focusing on a task while suppressing distractors may deplete cognitive resources. However, natural environments facilitate recovery from cognitive fatigue because nature evokes sufficiently gentle bottom-up attention [33]. The stimulus-driven involuntary attention is more autonomous than directed attention. Thus, nature can improve self-regulation and directed-attention capacity [34, 35]. Gradual shifts in dynamic lighting may operate in a similar manner. Natural scenes promote activity in the anterior cingulate cortex (ACC) and the insula [36], which underlie control and autonomous regulation during dynamic stimulation [30]. Moreover, different types of dynamic light may have a distinct effect, as in the present study the increasing sunlight condition was significantly better than static sunlight condition whereas decreasing sunlight was relatively weak in neurological or subjective markers. Previous work has shown that lighting impacts on alertness has a history effect. Exposure to high lux lighting has a greater and longer alerting response, followed by low lux compared to high lux lighting [37]. This study had participants exposed to lighting conditions for 6 hours. Our study showed a short-term effect. Other studies examining dynamic shifts in stimuli demonstrated this temporal context effect: perception of previous stimuli influences current perception and judgment on facial expression, emotional images, or auditory stimuli [38, 39, 40]. The temporal dependency might relate to sensitivity and adaptation; specifically, different dynamic stimuli and self-regulation might interact on neural responses and emotional processing. Increasing or de-

creasing lighting as a whole as a metaphor of sunrise and sunset, indicating a distinct need for human being in adapting to the environment.

### *Limitations and future study*

One of the limitations of the study is that we did not test the aftereffect of cognitive performance after each stress recovery condition. Ideally one would examine directed-attention capacity using some tasks of short-term memory or cognitive inhibition. Besides, we do not know if purely dynamic lighting in a short time would facilitate stress recovery in a relatively longer timeframe. Future studies should focus on the physiological mechanisms underlying restorative effects of dynamic natural environmental conditions. We also need more work on understanding which of the dynamic features mediate the restorative effects. For instance would nature sounds combined with virtual nature have different activation capabilities [41].

The present study calls attention to the possibility to obtain positive long-term health effects and cognitive performance with relatively brief exposures to dynamic lighting conditions. In my study, 30 seconds blank screen recovery phase was not sufficiently long enough for participants to fully recover from stress physiologically. However, increasing sunlight brightness could reduce more of skin conductance and EEG beta power. Stress responses occur across multiple biological response systems, such as cardiovascular, autonomic nervous system, hypothalamic-pituitary-adrenal (HPA) axis, and inflammatory responses. For example, the rate of cortisol stress recovery is associated with variations in metabolic risk and life stress [42]. We need to study the long-term benefits of repeated short-term stress recovery facilitated with dynamic nature lighting on the stress response systems in the body in addition to brain function.



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APPENDIX A  
CHAPTER 1 OF APPENDIX

*Reference*

Cohen, S., Kamarck, T., & Mermelstein, R. (1994). Perceived stress scale. *Measuring stress: A guide for health and social scientists*, 10.

*Instructions and Items*

The questions in this scale ask you about your feelings and thoughts during the last month. In each case, you will be asked to indicate by circling *how often* you felt or thought a certain way.

0 = Never, 1 = Almost Never, 2 = Sometimes, 3 = Fairly Often, 4 = Very Often

- In the last month, how often have you been upset because of something that happened unexpectedly?
- In the last month, how often have you felt that you were unable to control the important things in your life?
- In the last month, how often have you felt nervous and “stressed”?
- In the last month, how often have you felt confident about your ability to handle your personal problems?
- In the last month, how often have you felt that things were going your way?
- In the last month, how often have you found that you could not cope with all the things that you had to do?

- In the last month, how often have you been able to control irritations in your life?
- In the last month, how often have you felt that you were on top of things?
- In the last month, how often have you been angered because of things that were outside of your control?
- In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?



APPENDIX B  
CHAPTER 2 OF APPENDIX

*Reference*

Gross, J.J., & John, O.P. (2003). Individual differences in two emotion regulation processes: Implications for affect, relationships, and well-being. *Journal of Personality and Social Psychology*, 85, 348-362.

*Description of Measure*

A 10-item scale designed to measure respondents' tendency to regulate their emotions in two ways: (1) Cognitive Reappraisal and (2) Expressive Suppression. Respondents answer each item on a 7-point Likert-type scale ranging from 1 (strongly disagree) to 7 (strongly agree). Note: the authors request that researchers do not change the order of the items.

*Instructions and Items*

We would like to ask you some questions about your emotional life, in particular, how you control (that is, regulate and manage) your emotions. The questions below involve two distinct aspects of your emotional life. One is your emotional experience, or what you feel like inside. The other is your emotional expression, or how you show your emotions in the way you talk, gesture, or behave. Although some of the following questions may seem similar to one another, they differ in important ways. For each item, please answer using the following scale:

1 = strongly disagree ... 4 = neutral ... 7 = strongly agree

- When I want to feel more positive emotion (such as joy or amusement), I change what I'm thinking about.
- I keep my emotions to myself.
- When I want to feel less negative emotion (such as sadness or anger), I change what I'm thinking about.
- When I am feeling positive emotions, I am careful not to express them.
- When I'm faced with a stressful situation, I make myself think about it in a way that helps me stay calm.
- I control my emotions by not expressing them.
- When I want to feel more positive emotion, I change the way I'm thinking about the situation.
- I control my emotions by changing the way I think about the situation I'm in.
- When I am feeling negative emotions, I make sure not to express them.
- When I want to feel less negative emotion, I change the way I'm thinking about the situation.