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PSYCHOPHYSIOLOGY OF MOTIVATION: COMPETING SOCIAL AND BODILY NEEDS

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COLLEEN WOHLRAB

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For Margot,

My wife and best friend

Table of Contents

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

From subtle shifts in satiety cues to alterations in social dynamics, organisms manage an extensive set of environmental demands. Individuals must anticipate and respond to these shifts in their ever-changing environments to promote survival. Motivational processes coordinate physiological and behavioral prioritization driven by current and anticipated needs. Often as one motivation increases, organisms de-prioritize other motivational processes and shift resources towards behavioral and physiological processes associated with the most pressing needs. This dissertation provides a multi-level analysis of motivation across contexts, focusing on hunger, fatigue, and loneliness. I investigated how individuals dynamically shift physiological resources to meet current needs by examining autonomic physiology during motivational competition. Study 1 focuses on the autonomic correlates of mental and physical fatigue. Data from Study 1 demonstrate that prolonged mental fatigue may increase parasympathetic activity and decrease sympathetic activity. Physical fatigue was associated with rapid sympathoexcitation and parasympathetic withdrawal. Study 2 focuses on hunger and competing need states, demonstrating that brief fasting may increase resting parasympathetic nervous system activity. Finally, Study 3 investigates loneliness and motivated cognition. Results from Study 3 are a departure from past work on the topic, demonstrating that moderate levels of perceived social isolation may not motivate shifts in social cognition. Taken together, these three studies underscore the dynamic nature of psychophysiological systems and motivate future investigation into how social and non-social motivational processes interact.

CHAPTER 1:

GENERAL OVERVIEW AND INTRODUCTION

1.1 Maintenance of Stability through Change

Our world is incredibly dynamic. From subtle metabolic shifts to navigation of social networks, organisms manage an extensive set of environmental demands. Individuals constantly anticipate and respond to cues in their rapidly shifting world to promote survival. To partially account for constant fluctuations in the external environment, organisms often shift physiological and psychological processes to meet current needs. To avoid threats and promote survival, individuals must manage an expansive set of goals, including monitoring basic satiety cues associated with hunger, protecting the body from harm when fatigued, and maintaining positive social relationships.

Remarkably, under constant environmental stress, bodily systems generally remain stable (Gross, 1998). From the time of Hippocrates (Cofer & Appley, 1964), individuals have been hypothesizing about how bodily systems remain stable in the face of constant environmental change. When describing the constancy of physiological systems, 19th-century French physiologist Claude Bernard noted that systemic stability is partly due to internal states compensating for external environmental variability (Bernard, 1879). Bernard's theory about internal constancy was underappreciated during his lifetime. However, Bernard's work has framed much of modern psychophysiological theory. Inspired by Bernard's theory, American physiologist Walter Cannon later coined the term homeostasis. Homeostasis is an automated process by which biological systems maintain stability through internal physiological shifts in response to shifts in the external environment (Billman, 2020). Blood pressure maintenance is a classic example of a homeostatic regulatory process. Variations in blood pressure reflect a

response to environmental stressors aimed at maintaining cardiovascular homeostasis. Arterial blood pressure is maintained in a narrow band of values through a negative feedback loop via the activation of brainstem-mediated reflex adjustments (Adolph, 1961), modulated by arterial and cardiopulmonary reflexes. However, not all regulatory processes can be maintained with relatively simple homeostatic feedback loops.

Psychophysiological regulatory mechanisms encompass many levels of control extending from lower reflexes to higher-order control of behavior, emotion, and cognition. Cannon's homeostatic set-point model may not sufficiently account for the intricacy and multiplicity of systems that an organism must manage for survival. Systems within an organism do not exist in a vacuum and need to be able to coordinate shared resources flexibly. Moreover, waiting to react leaves individuals vulnerable to environmental threats. Organisms have evolved dynamic neurobehavioral systems beyond comparatively simple homeostatic regulatory processes (Goldstein & McEwen, 2002). Through the evolution of higher-order brain structures, organisms across species have developed the capacity to anticipate environmental perturbations (Schulkin et al., 1994). Not only can organisms respond to environmental stressors, but they can also learn from past stressors and prepare for future stressors. The ability to anticipate environmental stressors is advantageous because many environmental stressors occur rapidly and sometimes without warning. Additionally, learning from past exposure to stressors allows individuals to prepare for similar stressors in the future.

Allostasis is generally defined as maintaining constancy through change (McEwen & Wingfield, 2003). Through allostatic regulatory processes, organisms can change the levels of one or more physiological parameters to adjust to new or changing environments. Learning and anticipatory actions are core features of allostasis. Allostasis allows individuals to learn to

predict stressors and facilitate psychophysiological coordination in response to unpredictable, stressful events. Rather than physiological parameters having invariant set points, the value of a variable can and should change to cope with the demands presented by environmental changes.

1.2 Motivation

One of the ways that organisms manage behavioral selection is through the generation of motivational programs. Broadly, motivation represents an organism's willingness to expend or conserve energy to reach a goal (Cosmides & Tooby, 2000). Motivational systems take environmental context into account and rapidly shape behavior by prioritizing current needs. For example, if an animal is hungry, it will often endure a higher than average risk and expend greater than the typical effort to obtain and consume food (Dixon et al., 2014). When an individual is satiated, motivation shifts energetic resources away from food procurement and onto maintenance of other essential processes. Additionally, motivation influences the perception of environmental stimuli. For example, when hungry, individuals perceive food as tastier and better smelling than when satiated (Janowitz & Grossman, 1949).

Shifts in motivational states are not purely related to an organism's willingness to expend energy on singular goals due to ever-changing environmental context and need states. An organism's internal systems must simultaneously account for perturbations in other internal systems and the external world. As individuals have an abundance of needs that must be simultaneously addressed, motivational processes are often conflicting. For example, when dams (female rats) undergo an immune challenge, they must simultaneously manage maternal care responsibilities and mount an immune response. The dam's sickness response is a brain-derived motivational program for energy conservation. When the dam is sick, the sickness response conflicts with her motivational program associated with maternal care. While undergoing an

immune response, dams will decrease certain maternal care behaviors at ambient temperatures but engage in these caretaking behaviors at colder temperatures when her pups especially need warmth (Aubert et al., 1997). The results from this experiment indicate that social motivation to care for pups is flexible and responsive to shifts in both her internal environment (i.e., sickness) and external environment (i.e., temperature of housing). These results also demonstrate the profound influence of social motivation and how bodily needs can become deprioritized in the face of social needs.

Social engagement allows individuals to survive and prosper through information transfer, labor division, and defense from predation. Recent evidence demonstrates that social needs are comparable to hunger and thirst for survival (Dunning, 2011). Social goals, such as connecting with conspecifics, directly fulfill many other safety and physiological needs, such as hunger and fatigue. For example, social interactions involve communication about the whereabouts of food and division of labor to ease the burden on individual group members.

Studying competing motivational processes inherently necessitates investigation at multiple levels of analysis. Motivational processes require coordination of cognitive, affective, behavioral, and physiological systems. Psychological and social processes that support goal attainment cannot be completely understood without investigation of the underlying physiological systems that support and maintain psychological functioning. Likewise, we cannot wholly understand human systemic physiology without understanding an individual's social and psychological context. Throughout this dissertation, I will demonstrate how measuring and analyzing psychophysiological processes across multiple levels of analysis promotes a more complete understanding of phenomena.

1.3 The Autonomic Nervous System

The Autonomic Nervous System (ANS) innervates most organs in the human body and mediates the neural regulation of allostasis (Blessing & Gibbins, 2008). The ANS extends from the brain to the body's periphery and maintains allostasis in response to and anticipation of stressors within the body and the external world (McEwen & Wingfield, 2003). The ANS generally operates involuntarily and promotes the flexible and efficient distribution of bodily resources. The ANS also operates rapidly, on the order of milliseconds, allowing organisms to change physiological activation patterns quickly in response to shifting needs (Kreibig, 2010; McCorry, 2007). When describing the ANS, Walter Cannon wrote that the system was named "autonomic" because it acts automatically, without direction from the cerebral cortex (Cannon, 1939). While the ANS generally operates outside of an individual's conscious awareness, Cannon was incorrect about the cortex's involvement in ANS signaling. Lower-order neural regions that mediate ANS functioning extensively communicate with the cortex, modulating lower-level neural projections. For example, psychological stressors can promote baroreflex inhibition through higher order neural signaling. The baroreflex is a key mechanism for the control of blood pressure. Psychological stressors suppress the capacity of the arterial baroreflex to control short-term fluctuations in blood pressure. Neuroimaging data in humans demonstrates that reduced baroreflex sensitivity covaries with increases in neural activity in the CAN. (Gianaros et al., 2012).

The ANS has two branches: the parasympathetic nervous system (PNS) and the sympathetic nervous system (SNS). The preganglionic neurons of the sympathetic branch contain relatively short axons that terminate on the sympathetic chain ganglia. Parasympathetic preganglionic fibers contain long fibers that terminate on ganglia on peripheral organs (Wehrwein et al., 2016). As neural circuitry between the central nervous system (CNS) and the PNS in the periphery is

5

bidirectional, the brain receives visceral feedback through the vagus nerve, the primary nerve of the PNS. Cardiac function is jointly regulated by the PNS and the SNS, allowing for separate measurements of each branch at the level of the heart (Norman et al., 2014). The SNS provides excitatory cardiac input and often sympathetic activity increases in response to environmental stressors. SNS activity facilitates elevated cardiovascular activity and promotes affective and behavioral reactions aiding in goal attainment. The PNS, in contrast, provides tonic inhibitory cardiac control and promotes inhibition of reflexive reactions, enabling more elaborate processing of affective and behavioral responses (Thayer & Lane, 2009a). In some contexts, PNS activity indexes higher level neural inhibition necessary for flexible modification of psychophysiological processes. For example, cognitive reappraisal of negative emotions is associated with increases in PNS activity (Butler et al., 2006). Higher resting PNS activity is also associated with improved emotion regulation (Smith et al., 2017) and reduced feelings of social isolation (Quintana et al., 2013).

The Central Autonomic Network (CAN) comprises the set of brain regions involved in autonomic modulation and control (Sklerov et al., 2019). The CAN is an intricate network of brainstem, limbic, and prefrontal regions implicated in both resting ANS functioning and the modulation of ANS activity in response to and anticipation of environmental stressors. While there is not a universal consensus on which neural structures comprise the CAN, primary structures within the CAN include the insula, amygdala, hypothalamus, periaqueductal gray matter, parabrachial complex, the nucleus of the tractus solitarius, and ventrolateral medulla. The hypothalamus integrates autonomic functioning throughout the CAN, and the anterior limbic circuit integrates bodily sensations with emotional and goal-related autonomic responses (Sklerov et al., 2019).

CAN modulation is one way in which motivation aids in the maintenance of allostasis. Environmental cues associated with current needs are bidirectionally communicated between the

CNS and ANS, prompting rapid behavioral changes to support goal attainment (Lang, 2010). For example, hunger and immune cues are partially relayed to the brain through the vagus nerve (Cortelli et al., 2013; Drazen & Woods, 2003; Wang et al., 2002), the principal nerve of the parasympathetic nervous system (Thayer & Sternberg, 2006). Prefrontal and limbic neural structures process sensory information when integrating internal and external environmental cues for behavioral prioritization (Groenewegen & Uylings, 2000). For example, inhibitory projections from the prefrontal cortex to limbic structures aid in behavioral prioritization when integrating internal and external environmental cues (Thayer, 2006). Additionally, communication from the CAN to prefrontal cortical and motor brain regions directs behavioral responses essential for regulating processes such as emotion regulation and social behavior (Thayer & Lane, 2009b).

1.4 The Current Work

This dissertation describes three studies that examined competing motivational processes across contexts. Through this body of research, I aim to demonstrate the breadth of functions motivation plays in an individual's ability to flexibly adapt to their environment. Focusing on fatigue, hunger, and loneliness, I will discuss how physiology, behavior, and cognition adaptively shift in anticipation of and response to an organism's needs. Fatigue, hunger, and loneliness are all protective and motivate maintenance of allostasis. Mental and physical fatigue motivate individuals to end non-rewarding tasks and reorient resources towards more pressing needs. Hunger motivates the consumption of food and aids in the metabolic maintenance of allostasis. Loneliness motivates engagement with the social world and protects against the deleterious effects of chronic perceived social isolation. I will also describe how the measurement of autonomic cardiac physiology can aid in elucidating our understanding of

7

resource prioritization. The Autonomic Nervous System (ANS) mediates the neural regulation of allostasis (Blessing & Gibbins, 2008) and aids in the rapid distribution of physiological resources in support of goal attainment. Autonomic measures included in two of my studies index efferent neural signaling and provide insight into how the ANS may shift when an individual is hungry and fatigued.

Study 1 investigates how mental and physical fatigue relate to parasympathetic and sympathetic nervous system activation patterns. I induced mental and physical fatigue in this experiment and examined how autonomic patterns shift during fatigue induction. Study 2 examined motivational competition between hunger, pain, and sensitivity to pain in others. Study 2 also investigated if hunger, manipulated through fasting, influences behavior and autonomic physiology. Finally, Study 3 investigated how loneliness may impact cognitive functioning. This study used a loneliness induction paradigm and examined attentional biases and working memory capacity with social and non-social stimuli.

CHAPTER 2: FATIGUE AND THE AUTONOMIC NERVOUS SYSTEM

2.1 Introduction

Fatigue is associated with an overwhelming and sustained sense of exhaustion and decreased capacity for physical and mental work (van der Linden, 2011). Additionally, fatigue represents a decrease in motivation to continue an unrewarding activity when required to sustain high levels of effort over long periods (Hockey & Hockey, 2013). Mental fatigue is described as feelings of tiredness and lack of energy during or following prolonged periods of demanding mental activity (Boksem & Tops, 2008). However, mental fatigue can also arise due to insufficient stimulation and may thus also be associated with other states, such as boredom and drowsiness (Gawron et al., 2001). Physical fatigue generally refers to exhaustion from physical exertion (Tanaka & Watanabe, 2012). Mental fatigue and physical fatigue have historically been examined in separate bodies of literature. However, mental and physical fatigue are associated with the motivation to stop or downregulate effort while engaging in effortful tasks and reorientating resources towards goals associated with more pressing needs or more significant rewards.

The impact of mental fatigue on subsequent physical performance has been well documented in recent years. Several studies have demonstrated that physical performance is negatively affected when preceded by mental fatigue induction (Brown et al., 2020; Marcora & Staiano, 2009; Mehta et al., 2013). For example, when a physically demanding task follows mental fatigue induction, behavioral and self-reported measures of physical fatigue are higher than when the physically fatiguing task is performed independently (Cutsem et al., 2018). Performance deficits and heightened reports of perceived exertion following mental fatigue induction have spanned various exercise types. Mental fatigue particularly impacts endurance

performance (e.g., long runs, bikes, or swims) possibly due to the noradrenergic neurotransmitter system hastening central fatigue and speeding the rating of perceived exertion (Cutsem et al., 2017). The current theoretical explanation for these findings posits that effort from mental fatigue carries over into the perception of effort during physical performance tasks (Cutsem et al., 2017). Heightened perception of effort at the start of physically fatiguing tasks results in heightened fatigue throughout the physical performance and promotes the motivation to end the physical performance task. Also, recent evidence suggests that physical performance deficits when mentally fatigued may be caused by a decreased capacity for dopamine and norepinephrine reuptake following cognitive fatigue (Meeusen & Roelands, 2018).

Mental and physical fatigue may partially share neural mechanisms. The Anterior Cingulate Cortex (ACC) is an integral component of the limbic system and is associated with cognitive and emotional processes, such as attentional and emotional regulation (Bush et al., 2000). Past work suggests that activation of the ACC relates to both cognitive load associated with mental fatigue and the perception of effort during exercise associated with physical fatigue (Tanaka et al., 2014). The anterior insula is associated with deliberative processes associated with the exertion of mental effort (Müller & Apps, 2019). The anterior insula also processes interoceptive bodily signals associated with muscle fatigue, increasing motivation to stop an effortful task (Liu et al., 2002). The anterior insula is a critical component of a recently described 'fatigue network' associated with mental work (Wylie et al., 2020). This network monitors internal bodily states and evaluates the value of pursuing the current course of action given current needs. Additionally, research in clinical populations has helped uncover the crucial role played by the cortico-striatal reward circuitry in fatigue (Dobryakova et al., 2013). Recruitment

of reward circuitry indicates that the amount of effort expended on a fatiguing task may depend on the perceived reward expected from completing the task.

Motivational programs, such as fatigue generation are partially directed through bidirectional processing between the central and peripheral nervous systems. Activation of the ANS is one mechanism through which resources can be rapidly shifted around to meet current demands and maintain stability within an organism. The ANS extends from the brain to the body's periphery and maintains internal stability in response to and anticipating stressors from the internal and external environment (McEwen & Wingfield, 2003). The relationship between ANS activity, upstream neural activity, and behavioral prioritization is primarily explained by the bidirectional flow of information throughout the Central Autonomic Network (CAN) (Benarroch, 2012), the neural network principally responsible for the control of the ANS. Feedback and feedforward signals processed within the CAN, such as the ACC and insula, regulate the intensity of physical fatigue to ensure that the effort exerted is tolerable (McMorris et al., 2018). Predictions of fatigue related sensory information are fed forward by dorsolateral prefrontal cortex (DLPFC) projections to the insular cortex. The feedback is compared to the predictions in order to generate an awareness of fatigue level, which is forwarded to the ACC. Finally, the LPFC integrates information to make a decision as to whether to continue or stop the effortful activity (McMorris et al., 2018).

Examining peripheral physiological mechanisms during mental and physical fatigue induction may partially elucidate the physiological mechanisms associated with the well-documented psychological phenomena associated with fatigue. The physiological mechanisms by which fatigue during mentally taxing tasks impact fatigue during physical tasks are not yet clearly established. Psychophysiological regulatory mechanisms associated with fatigue

11

encompass many levels of control, extending from lower reflexes to higher-order control of behavior, emotion, and cognition. As fatigue involves affective, cognitive, behavioral, and autonomic components measurement at multiple levels of analysis provides a more complete understanding of phenomena. While there are undoubtedly other neural regions activated during cognitively and physically demanding tasks, examining the efferent flow of information from the CAN has particular relevance for the study of fatigue. Examination of autonomic activity during effortful tasks also provides additional insight into the temporal nature of fatigue generation. Autonomic activation patterns rapidly fluctuate on the order of milliseconds. Measurement of the Parasympathetic Nervous System (PNS) and Sympathetic Nervous System (SNS) thus allows us to precisely determine when autonomic activation patterns shift and examine how this corresponds to when an individual reports feeling fatigued.

The current study expands on existing work demonstrating how mental fatigue impacts subsequent physical performance. There is no robust physiological evidence that explains how and why mental fatigue impacts physical fatigue and performance. Uncovering a relationship between fatigue and autonomic physiology will provide insight into medical conditions associated with fatigue and provide additional insight into why this phenomenon occurs. Gaining a better understanding of physiological shifts associated with fatigue helps explain why fatigue motivates individuals to stop effortful tasks. Indeed, examining the physiological correlates of fatigue provides insight into how organisms prioritize physiological resources to protect the body from harm. Past work has demonstrated that mental fatigue caused by the prolonged cognitive load is associated with sympathetic hyperactivity (Mizuno et al., 2011) and decreases in PNS activity (Zhang & Yu, 2010). Caveats of these works include small sample sizes and inconsistent techniques used to derive estimates of autonomic cardiac control. However, there is a well-

established relationship between physical fatigue and autonomic activation patterns. Generally, as physical fatigue rises, PNS activity falls, and SNS activity rises (Arai et al., 1989; Gronwald et al., 2018), which would match the effects of the past studies on mental fatigue. While there appears to be a shared directional relationship between ANS activation patterns of physical and mental fatigue, little is known about how these activation patterns relate to the broader shared psychological features of mental and physical fatigue or why mental fatigue exasperates physical fatigue.

I aimed to partially elucidate the relationship between ANS activity and perceived fatigue during mentally and physically fatiguing tasks. First, I sought to confirm that the tasks induced fatigue by examining mental fatigue and perceived exertion throughout the mentally and physically fatiguing tasks. I then examined the temporal dynamics of ANS activity during mental fatigue induction, hypothesizing that SNS activity would rise and PNS activity would drop throughout the physical fatigue task. Past work has demonstrated that prolonged cognitive load is associated with increased SNS activity and decreased PNS activity (Mizuno et al., 2011). Mentally fatiguing tasks, such as the Stroop Task, have also been related to decreased PNS activity and increased SNS activity (Hoshikawa & Yamamoto, 1997). Likewise, I predicted that PNS activity would drop and SNS activity would rise during mental fatigue induction (Fisher et al., 2015). I then examined if ANS activity during mental fatigue induction predicted ANS activity during subsequent physical exertion. As past work has demonstrated that mental fatigue is associated with shifts in ANS activity (Mizuno et al., 2011) and impairs performance on subsequent physically fatiguing tasks (Marcora & Staiano, 2009), I hypothesized that the magnitude of ANS activity changes throughout the mentally fatiguing task would predict the magnitude of change in ANS activity throughout the physically fatiguing task. I also examined

how PNS and SNS shifts map onto behavioral and self-reported mental and physical fatigue measures, with the hypothesis that shifts in ANS activity would be strongly correlated with behavioral and self-reported measures of fatigue. This hypothesis was again based on past work demonstrating the relationship between ANS activity and fatigue induction (Fisher et al., 2015; Mizuno et al., 2011).

2.2 Methods

2.2.1 Participants

The experiment was approved by the Institutional Review Board of the University of Chicago. Participants were recruited from the University of Chicago student population and the local community. 82 (48 female) University of Chicago and Chicago community members aged 18 – 35 (mean 21.94) were included in the final dataset. See Table 3.1 for a more detailed display of participant demographics and self-report measures. Participants provided informed consent and were provided monetary or course credit compensation for participation. Before enrollment in the study, participants were screened for a history of illnesses that would interfere with participation in the exercise task.

2.2.2 Procedure

Upon arriving at the laboratory, participants first completed the informed consent paperwork and a questionnaire assessing state affect. Next, the research assistant affixed electrodes to the participant's chest and back and began the continuous recording of autonomic cardiac activity. The participant then sat quietly for five minutes while I collected baseline autonomic activity. The participant was then left alone in the testing room for 90 minutes to complete the mental fatigue task. Next, the participant watched a 10-minute neutral video as a recovery period between the mentally fatiguing and physically fatiguing task. Participants

watched one of three videos: a video with natural scenery, urban scenery, or an animated video with neutral objects. The video that participants watched did not impact any of the analyses discussed below. The research assistant then provided detailed instructions for the submaximal exercise task and fit the subject with a heart rate monitor worn on the chest. Next, the participant completed the YMCA submaximal cycle ergometer test. The research assistant monitored heart rate in real-time to determine the progression of the ergometer test. The participant completed a series of self-report questionnaires (detailed below). Finally, the research assistant debriefed the participant about the study and answered any questions before compensating the subject and instructing them to depart the laboratory.

2.2.3 Self-Report Questionnaires

Measures of demographic variables, cognitive functioning, state and trait affect, and personality were collected via Qualtrics. Participants completed questionnaires including the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988a), the International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003), the Brief Fatigue Inventory (BFI) (Mendoza et al., 1999), and the Attentional Function Index (AFI) (Cimprich et al., 2011).

2.2.4 Mentally Fatiguing Task

Behavioral tasks were administered using E-prime 2.0. Stimulus presentation was displaced on a 24" monitor facing the participant, seated approximately 30" away. Immediately following baseline physiological data collection, participants completed a 90-minute mentally fatiguing task, the AX-Continuous Performance Task (AX-CPT). As cue-probe pairs, the A cue/X probe pair constitutes the target and occurs frequently; all other pair-types that require a nontarget response are examined with two types of lure trials, BX (an X probe not preceded by an A cue) and AY (an A cue not followed by an X probe). The AX-CPT has been previously

used to reliably induce mental fatigue (Cutsem et al., 2017; Macmahon et al., 2014). See Figure 2. 1 for example stimuli from the AX-CPT task.

2.2.5 Physically Fatiguing Task

Participants then completed a modified version of the YMCA sub-maximal ergometer test (Golding et al., 1989). The cycle ergometer task was administered using a Lode (Excalibur Sport, Corval Lode B.V., Lode Medical Technology, Groningen, Netherlands) cycle ergometer. Three or four consecutive 3-minute workloads were completed, depending on duration to exhaustion. Subjects performed cycle ergometry at a fifty revolutions/minute cadence, and the initial workload was 25 Watts. Heart rate during the last 15 seconds was used to determine subsequent workloads (if HR <80 beats/min:125 Watt; 80 to 90 beats/min:100 Watt; 90 to 100 beats/min:75 Watt; and >100 beats/min: 50 Watt). The test was terminated when the participant's heart rate reached 80% of the predicted max heart rate. Age-predicted max heart rate was calculated using the following formula: 0.8 * (208 - .7 * age) (Tanaka Hirofumi et al., 2001). Heart rate was monitored in real-time using a Polar H10 heart rate monitor and Polar Beat's corresponding software package. The Polar H10 band has been validated for excellent RR interval (the time elapsed between two successive R-waves of the QRS signal on the electrocardiogram) signal quality throughout various activities (Gilgen-Ammann et al., 2019). Physical exertion was assessed every minute by assessing the Rate of Perceived Exertion (RPE) through Borg's rating scale of perceived exertion (the scale ranged from 6 ("No Exertion at All") to 20 ("Maximal Exertion")) (Borg, 1982). RPE was normalized to the percent of maximum possible for analyses. See Figure 2. 2 for greater detail on the YMCA Submaximal ergometer task procedures.

2.2.6 Measurement of the Parasympathetic Nervous System

A standard lead II configuration was used for obtaining the electrocardiogram (ECG). Data was collected using a BioNex two-slot mainframe (Mindware Technology, Gahanna, OH) connected to a laptop computer. Time stamping triggers were integrated into the behavioral task scripts to provide millisecond resolution for the cardiac and behavioral data. We sampled the ECG signal at 1000 Hz. The ECG signal was analyzed using Mindware Technology's HRV software, Version 3.10. Visual inspection and manual data editing were completed to ensure proper artifacts and ectopic heartbeat removal.

Respiratory sinus arrhythmia (RSA) is a phenomenon associated with heart rate fluctuation within the respiratory frequency band. RSA refers to the speeding and slowing of the heart via the vagus nerve, the principal nerve of the PNS. High-frequency heartrate variability (hf-HRV) (a measure of RSA) was derived by spectral analysis (Mindware HRV software, Version 3.1.5) of the interbeat interval series obtained from the ECG. The interbeat interval series was time-sampled at 4 Hz to obtain an equal interval time series that was detrended, end-tapered and submitted to a Fast Fourier Transform, which then was integrated over the respiratory frequency band (0.12 – 1.0 Hz). Typically, 0.12 – 0.42 Hz is considered the standard respiratory frequency band, as it corresponds to normative deviations in respiration rate at rest (7 to 24 RR (breaths/minute)). We chose to extend the frequency band for this experiment because participants frequently exceeded 24 RR during the physically fatiguing task.

2.2.7 Measures of the Sympathetic Nervous System

Pre-ejection period (PEP) derived from impedance cardiography is the period between the electrical invasion of the ventricular myocardium (Q wave of the ECG) and the aortic valve opening. PEP depends on the time development of intraventricular pressure; it is widely used as

an index of myocardial contractility. Because variations in contractility are primarily under sympathetic control, PEP is commonly used as a noninvasive measure of sympathetic cardiac control (J. T. Cacioppo et al., 1994). Lower PEP values represent higher levels of sympathetic cardiac control. PEP values are represented in milliseconds.

2.2.8 Data Analysis Plan

All analyses were run with and without age, gender, and ethnicity as covariates. The demographic variables did not impact model significance. Model results are reported without demographic variables included. Data cleaning and manipulation were done using the dyplyr package (Mailund, 2019). Visualizations were generated using Microsoft Excel. Multi-level models were run using the lme4 package (Bates et al., 2007, p. 4). Subjects were included as a random factor in all repeated measure MLMs. All predictors in regression models were standardized using the scale function in base R. Repeated measure correlations were generated using the rmcorr package (Bakdash & Marusich, 2017). All other models were generated in base R. Autonomic, and behavioral values +/- 3SD from the mean were excluded from analyses.

2.3 Results

2.3.1 Participant Exclusion

We recruited and ran 95 subjects through the procedure described above. Remarkably, all participants completed both the mental and physical fatigue tasks. A total of thirteen subjects were excluded from analyses, leaving us with 85 subjects in the final dataset. Four subjects were excluded for excessively low accuracy (greater than 3 SD less than the group mean) or excessive missing values from the mental fatigue task. Three subjects were excluded for incomplete or excessively noisy ANS data collected during the mental fatigue task. Six subjects were excluded for excessively noisy ANS data collected during the physical fatigue task.

18

2.3.2 Fatigue Induction Validation

Mental fatigue was significantly higher at the end of the mental fatigue task (M = 5.35, SD = 1.74) than at the start of the mental fatigue task (M = 2.80, SD = 1.39), t(153) = 10.34, p < 0.001. An MLM confirmed that that mental fatigue significantly increased with time during the mental fatigue task (β(82, 654) = 0.44, SE = 0.02, CI = [0.40, 0.48], p < 0.001). See Figure 2.3 for visualization of mental fatigue across time.

Physical fatigue, as proxied by perceived exertion, was significantly higher at the end of the exercise task (M = 16.70, SD = 2.81) than at the start of the exercise task (M = 7.58, SD = 1.65), t(118) = 9.50, p < 0.001. A hierarchical linear model confirmed that physical fatigue significantly rose with time during the exercise task (β(82, 778) = 0.84 SE = 0.02, CI = [0.81,0.87], p < 0.001). See Figure 2.4 for visualization of physical fatigue across time. On average, it took participants 44.7 (sd = 23.81) minutes to reach max mental fatigue and 9.2 (sd = 1.81) minutes to reach maximum physical fatigue.

2.3.3 ANS Activity throughout Fatigue Induction

PNS activity significantly rose throughout the mental fatigue task (β(82, 645) = 0.22, SE = 0.02, CI = [0.17, 0.26], p < 0.001) and significantly decreased throughout the physical fatigue task (β(82, 890) = -0.83, SE = 0.02, CI = [-0.86, -0.79], p < 0.001). See Figure 2. 3 and Figure 2. 4 for visualizations of these relationships, respectively. SNS activity significantly dropped throughout the mental fatigue task (β(79, 591) = -0.08, SE = 0.02, CI = [-0.04, -0.12], p < 0.001) and rose throughout the physical fatigue task (β(80, 689) = 0.48, SE = 0.03 ,CI = [0.43,0.53], p < 0.001). See Figure 2. 5 and Figure 2. 6 for visualization of these relationships, respectively.

2.3.4 ANS and AX-CPT Behavioral Measures

PNS activity and self-reported mental fatigue ratings were positively correlated, $r(567) = 0.30$, $p < 0.001$, and SNS activity was negatively correlated with mental fatigue, $r(503) = -0.16$, $p < 0.01$ throughout the mental fatigue task. See Figure 2. 3 and Figure 2. 5 for visualizations of these relationships. We found that task accuracy, an index of sustained attention, significantly dropped with time ($\beta(82, 1147) = -0.06$, $SE = 0.03$, $CI = [-0.12, 0]$, $p < 0.001$). Task accuracy was also negatively correlated with mental fatigue over time, $r(495) = -0.24$, $p < 0.001$. A repeated measure correlation revealed that our data do not show a significant relationship between PNS activity and task accuracy ($r(483) = -0.04$, $p > 0.05$) or SNS activity and task accuracy ($r(437) = -0.04.$, $p > 0.05$)

2.3.5 ANS and Physical Fatigue Task Behavioral Measures

PNS activity and self-reported physical fatigue ratings were strongly negatively correlated, $r(689) = -0.85$, $p < 0.001$, and SNS activity and self-reported physical fatigue ratings were strongly positively correlated, $r(563) = 0.52$, $p < 0.001$ throughout the physical fatigue task. See Figure 2. 4 and Figure 2. 6 for visualization of these relationships.

2.3.5 Relationship between mental and physical fatigue tasks

Time to reach maximal self-reported mental fatigue negatively predicted time to reach maximal self-reported physical fatigue ($r(82) = -0.23$, $p < 0.05$). See Figure 2.7 for a visualization of this relationship. PNS activity at maximal mental fatigue predicted PNS activity throughout the subsequent physical fatigue task. Subjects with higher PNS activity demonstrated steeper drops in PNS activity during the physical fatigue task than individuals with low PNS activity at maximal mental fatigue. Individuals with high PNS at maximal mental fatigue ended up with significantly lower PNS activity at the end of the physical fatigue task than individuals

with low PNS activity at maximal mental fatigue (β = 1.19, SE = 0.03, CI = [1.13, 1.25], p < 0.01). See Figure 2.8 for a visualization of this relationship.

There was no significant relationship between PNS activity r(292) = 0.05, p > 0.05) or SNS activity (r(219) = 0.05, p > 0.05) during mental and physical fatigue tasks, as measured by within-subject repeated measures correlations. There was also no significant relationship between self-reported fatigue during the mental and physical fatigue tasks, as measured by a within-subject repeated measure correlation (r(285) = -0.02, p > 0.05).

2.4 Discussion

We sought to examine how autonomic physiology shifts throughout fatigue induction. We induced both mental and physical fatigue through an in-lab experiment and measured both branches of the ANS. We found that rises in mental fatigue were strongly associated with rises in parasympathetic activity. This relationship between PNS activity and mental fatigue was counter to our predictions and previous work demonstrating an inverse relationship between PNS activity and mental fatigue. While some work has shown that mental fatigue may be associated with drops in PNS activity (Mizuno et al., 2014), other literature suggests that sustained attention is related to increases in PNS activity over time (Pattyn et al., 2008). Given the strong relationship between time, mental fatigue ratings, and PNS activity, we believe mental fatigue is driving the rise in PNS activity throughout the mental fatigue task. Cardiac autonomic measures typically remain stable at rest (Kleiger et al., 1991); if an individual were to sit in a chair for 90 minutes without completing the AX-CPT, it would be improbable for PNS activity to rise and SNS activity to drop as it did during our administration of the AX-CPT. This further demonstrates that mental fatigue is likely driving the shifts in autonomic activity described above. Additionally,

21

mental fatigue ratings were significantly related to rises in hf-HRV and drops in PEP during the mentally fatiguing task.

We also found that individuals who took longer to reach maximal self-reported mental fatigue took less time to reach maximal self-reported physical fatigue than individuals who took less time to reach maximal mental fatigue. This result may indicate that individuals who take longer to become mentally fatigued may be more prone to rapid physical fatigue induction due to a carry-over in perceived effort. Additionally, PNS activity at maximal mental fatigue predicted PNS activity decline during the physical fatigue task. Subjects with higher PNS activity demonstrated steeper drops in PNS activity during the physical fatigue task than individuals with low PNS activity at maximal mental fatigue. Individuals with high PNS at maximal mental fatigue ended up with significantly lower PNS activity at the end of the physical fatigue task than individuals with low PNS activity at maximal mental fatigue. This examination of within-subject PNS activity shifts partially elucidates the physiological relationship between mental and physical fatigue. ANS activation may be a mechanism through which MF influences physical performance during PF induction. As PNS activity rose throughout the mentally fatiguing task, it may be that individuals who demonstrated especially large increases in PNS activity during mental fatigue induction have greater autonomic flexibility, as demonstrated by the sharper drops in their PNS activity during the physically fatiguing task. One explanation for this finding is that individuals who demonstrate high PNS activity during intense cognitive stress have greater flexibility in overall autonomic activation patterns in response to mental and physical stressors.

Future work will investigate these relationships further and investigate individual differences in autonomic flexibility and if this is related to the magnitude of how fatigued an individual feels. Implications for our findings include a better understanding of the physiological

correlates of fatigue. Continuing to elucidate the physiological manifestation of fatigue will aid in diagnosing and treating fatigue-associated disorders such as chronic fatigue syndrome and depression. Future directions include examining any potential effects of physical fatigue on mental fatigue. Indeed, if mental and physical fatigue represent a single phenomenon, is it likely that physical fatigue may impact mental fatigue in the same way that mental fatigue impacts physical fatigue. A limitation of our study was that we did not have a control group of subjects who did not experience mental fatigue induction before physical fatigue induction. While there is ample evidence to suggest that mental fatigue impacts physical fatigue and performance (Cutsem et al., 2017), less is known about the potential impact of physical fatigue on mental fatigue and cognitive performance. While current work suggests that mental and physical fatigue may represent a heavily overlapping but separable construct, additional work may suggest otherwise. If physical fatigue impacts mental fatigue and cognitive performance, this will suggest that mental and physical fatigue represent a singular construct that shares physiological resources. Examining autonomic activity when physical activity precedes a mentally fatiguing task will complement our current analyses and provide additional insight into the psychophysiological regulatory mechanisms associated with fatigue.

2.5 Appendix A: Chapter 2 Tables and Figures
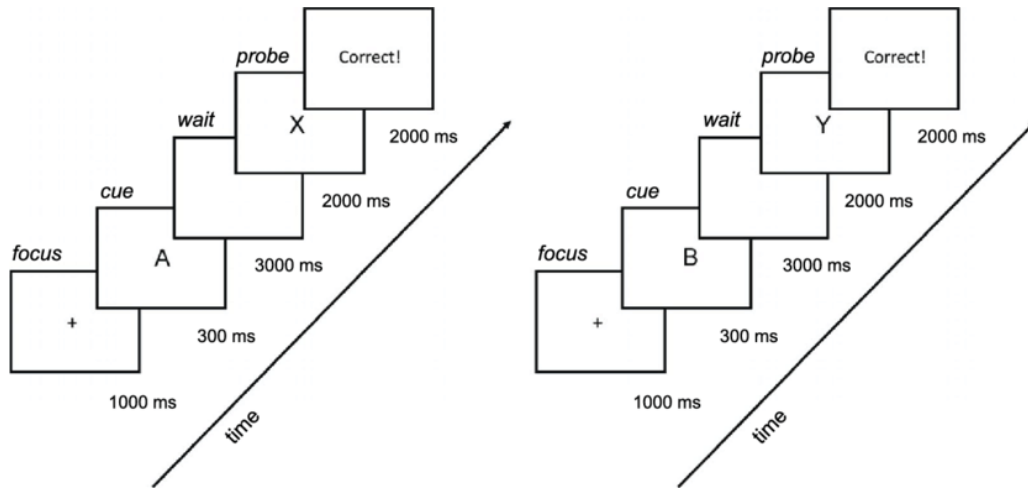
Figure 2. 1 Example stimuli from AX-CPT task
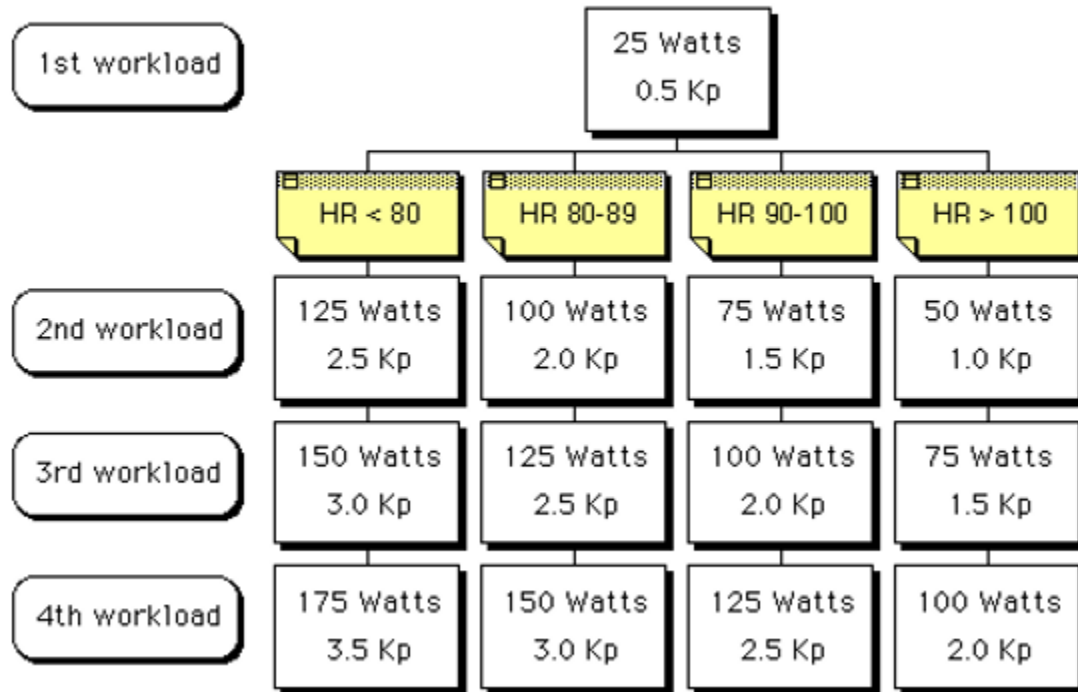
Figure 2. 2 YMCA Cycle Ergometer Protocol

(Garatachea et al., 2007)
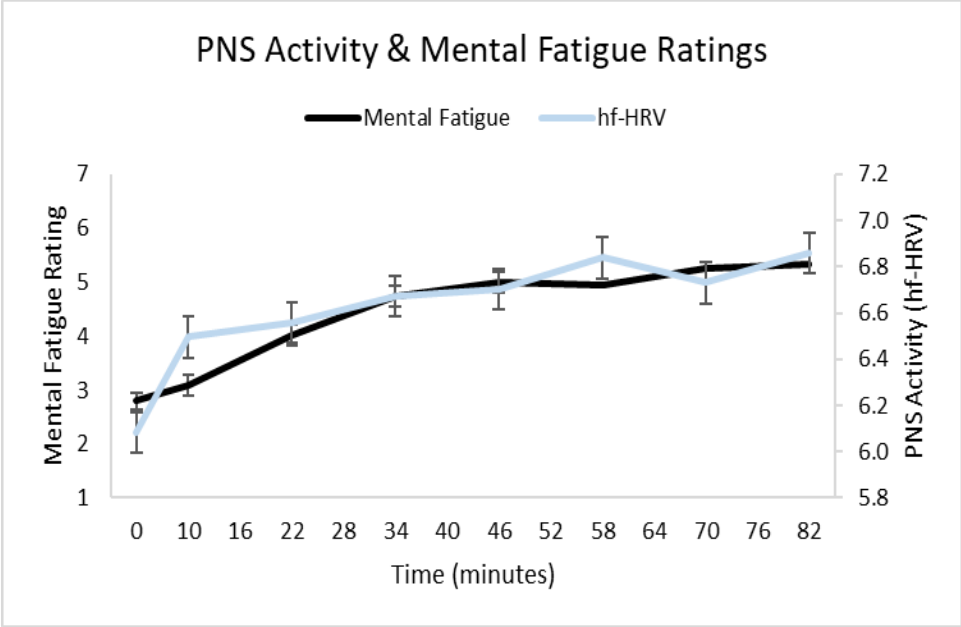
Figure 2. 3 Mental Fatigue Ratings and PNS Activity

Error bars represent the standard error of the mean. Mental fatigue increased linearly with time during the AX-CPT task. PNS activity (hf-HRV) also increased linearly with time throughout the AX-CPT task. PNS activity and mental fatigue ratings were significantly correlated over time $(r(567) = 0.30, p < 0.001)$. Error bars represent the standard error of the mean.
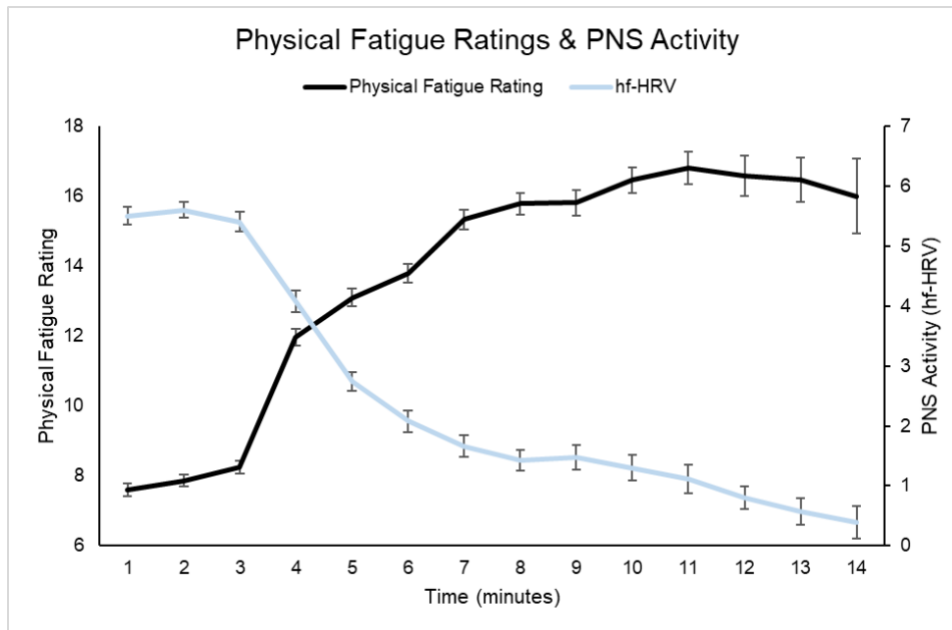
Figure 2. 4 Physical Fatigue Ratings and PNS Activity

Physical fatigue ratings increased (β = 0.84 SE = 0.02, CI = [0.81,0.87]) and PNS activity decreased with time (β = -0.83, SE = 0.02, CI = [-0.86, -0.79]) throughout the physical fatigue task. Physical fatigue ratings and PNS activity values were significantly negatively correlated over time (r(689) = -0.85, p < 0.001). Error bars represent standard error of the mean.
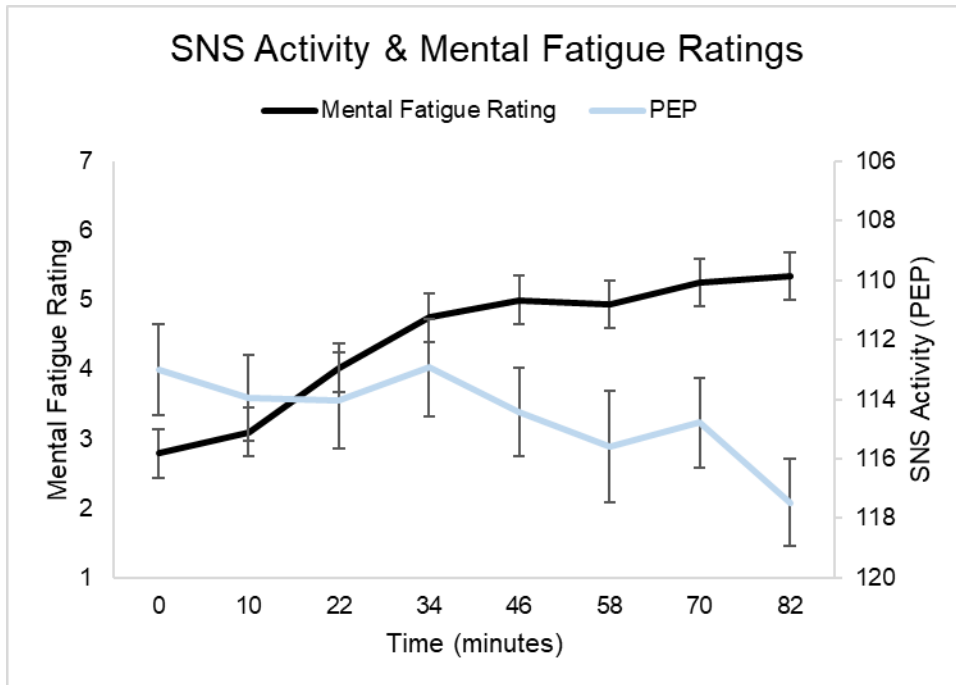
Figure 2. 5 Mental fatigue ratings and SNS activity

Mental fatigue ratings rose ($\beta = 0.44$, SE = 0.02, CI = [0.40, 0.48]) and SNS activity decreased ($\beta = -0.08$, SE = 0.02, CI = [-0.04, -0.12]) throughout time during the AX-CPT task. Mental fatigue ratings and SNS activity were significantly correlated over time during the AX-CPT task ($r(503) = -0.16$, $p < 0.01$). Error bars represent standard error of the mean. Y-axis reverse scored because lower PEP values represent higher SNS activity.
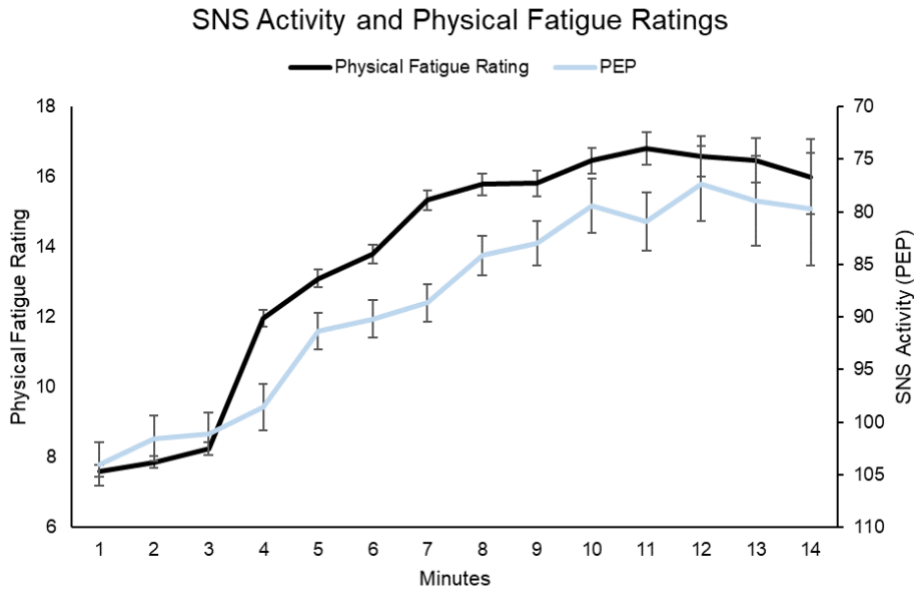
Figure 2. 6 Physical Fatigue ratings and SNS activity

SNS activity (β = 0.48, SE = 0.03 ,CI = [0.43,0.53]) and physical fatigue ratings (β = 0.84 SE = 0.02, CI = [0.81,0.87]) significantly rose over time during the cycle ergometer task. Physical fatigue ratings and SNS activity values were significantly positively correlated over time (r(563) = 0.52, p < 0.001). Error bars represent standard error of the mean. Y-axis reverse scored because lower PEP values represent higher SNS activity.
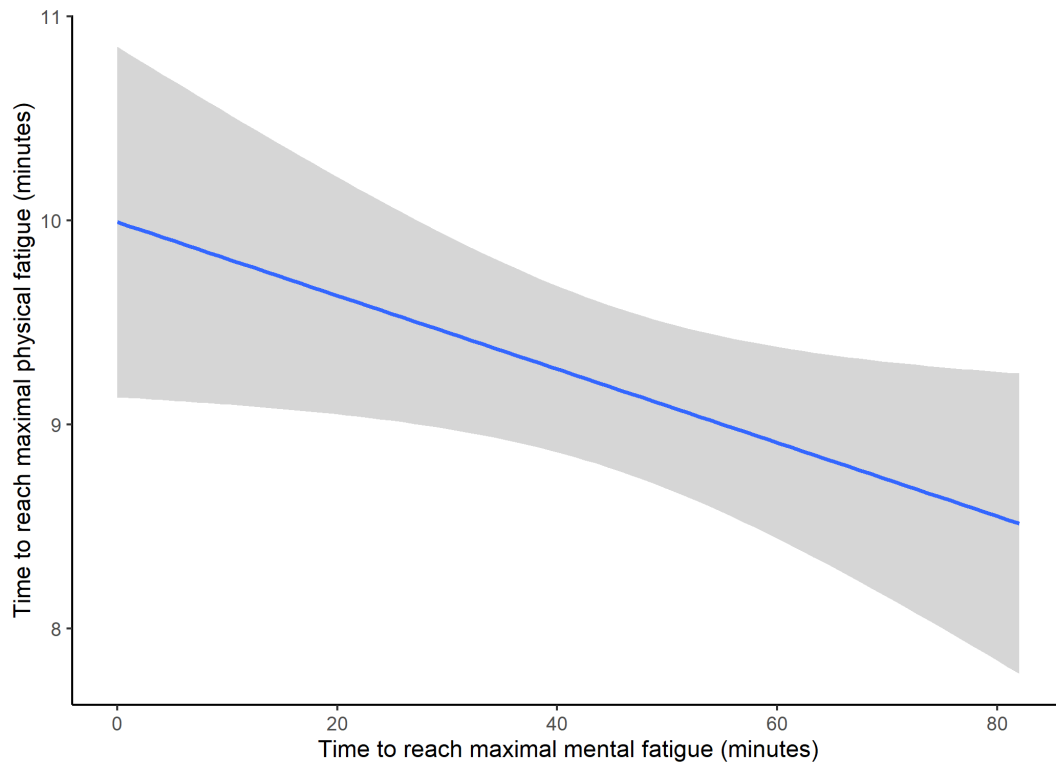
Figure 2. 7 Time to reach maximal physical fatigue, predicted by time to reach maximal mental fatigue

Time to reach max MF negatively predicted time to reach maximal physical fatigue ($r(82) = -0.23$, $p < 0.05$). The shaded region represents standard error of the mean.

PNS Activity during Physical Fatigue Task predicted by
PNS Activity during Mental Fatigue Task
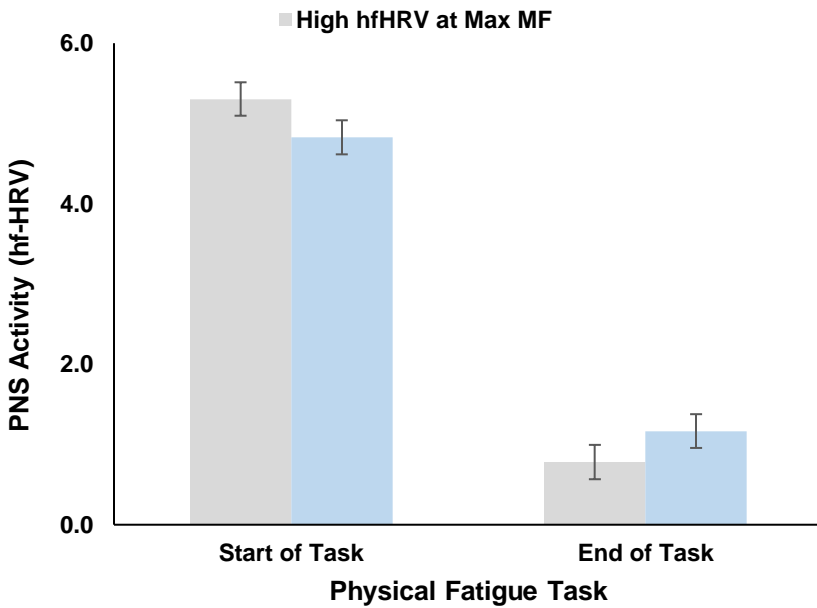
Figure 2. 8 PNS Activity during Physical Fatigue task predicted by PNS activity during Mental Fatigue Task

Subjects with higher PNS activity demonstrated steeper drops in PNS activity during the physical fatigue task than individuals with low PNS activity at maximal mental fatigue. Individuals with high PNS at maximal mental fatigue ended up with significantly lower PNS activity at the end of the physical fatigue task than individuals with low PNS activity at maximal mental fatigue ($\beta = 1.19$, SE = 0.03, CI = [1.13, 1.25], p < 0.01). Error bars represent standard error of the mean.

CHAPTER 3: PSYCHOPHYSIOLOGY OF HUNGER AND PAIN PERCEPTION

3.1 Introduction

Ingestion and metabolism of energetic resources are essential components of life (Dupré & O'Malley, 2013). Hunger generally refers to the motivation to seek and ingest food (Powley, 2009). As hunger increases, organisms are increasingly willing to expend effort and endure risks to forage and consume food. For example, hungry birds are more willing to cross a dangerous water barrier to access food than satiated birds (Dixon et al., 2014). Goals associated with hunger sometimes come at the expense of other processes (Gailliot, 2013). For example, extreme hunger can be associated with a decrease in water consumption (McFarland, 1964), demonstrating how current needs drive behavioral shifts (McEwen & Wingfield, 2003). Hunger is associated with allostatic perturbations, such as increases in plasma ghrelin and leptin (Campfield, 1996). Physiological shifts associated with hunger can be detected through awareness of internal visceral states, often felt in the abdomen (Friedman et al., 1999).

Interoceptive awareness refers to the perceived intensity of visceral sensations and is primarily processed through afferent signaling of visceral sensations from the ANS to the CNS (Critchley & Garfinkel, 2017). Perception of hunger is strongly influenced by how intensely an individual perceives visceral sensations of fullness (Stevenson et al., 2015). Consequently, individuals who are poor at matching bodily sensations associated with hunger to actual energy needs are prone to overeating and obesity (Simmons & DeVille, 2017). Sensory information related to hunger is processed in the hypothalamus, a key neural structure involved in activation of the ANS (Kreibig, 2010). When an individual is hungry, the ANS aids in restoration of allostasis through pancreatic adrenergic and cholinergic signaling, integral in regulation of insulin and glucagon (Havel & Taborsky, 1989).

We can better understand how internal and external environmental contexts impact motivation's flexibility by examining multiple motivational processes simultaneously. An individual has a finite number of resources to work with and needs to utilize these resources efficiently when multiple needs co-occur. Investigating co-occurring motivational states with strong bodily feeling states, such as hunger and pain, provides insight into how the strength of perception of physical sensations impacts the prioritization of motivational processes. Social context and visceral motivational processes, such as hunger and pain, often interact. For example, when an individual feels validated by a partner, pain ratings decrease during a pain tolerance task (Leong et al., 2015). Additionally, decreases nutrients in an individual's diet has been associated with increases in social punishment for norm violations (Strang et al., 2017). While not directly investigating hunger, this study causally demonstrated that altering the macronutrient components of a meal (i.e., low carbohydrate/high protein or high protein/low carbohydrate) influences an individual's willingness to tolerate social norm violations. hunger, pain, and empathy allows for a unique understanding of how motivation may be flexible to internal bodily shifts and social context.

Pain refers to the motivation to avoid actual or potential bodily damage (A. C. Williams & Craig, 2016). Many brain areas involved in the affective dimension of pain processing also modulate ANS activity. For example, the anterior insula receives input from the ANS and the spinothalamocortical pathway, which projects peripheral pain information to the CNS (Critchley et al., 2013; Leone et al., 2006). The tight connection between the pain processing system and the ANS allows the ANS to rapidly prepare the body for behavioral responses to pain (Leone et al., 2006). There is evidence that hunger may decrease chronic pain symptomatology in humans (Michalsen, 2010) and dampen behavioral and affective responses to chronic pain in rodents

(Alhadeff et al., 2018). There is also evidence that chronic pain may dampen hunger (Bosley et al., 2004). To the best of our knowledge, work directly examining the dynamic interactions between acute pain and acute hunger in humans has yet to be documented.

In mammals, empathy is crucial for living in social groups and caring for others (Decety et al., 2012). Empathy represents an ability to perceive and vicariously experience the emotions of others, at least in terms of valence and arousal (Decety, 2015). Humans utilize empathy to support interpersonal cooperation and navigation of social relationships (Rumble et al., 2010). Empathy motivates individuals to simulate and better understand others' emotions (Decety, 2011). Some evidence suggests that certain socially cooperative behaviors may be deprioritized under acute hunger states. For example, recent work has demonstrated that acute hunger decreases children's willingness to share resources (Huppert et al., 2020). While these behaviors may indicate a shifting of resources associated with empathy, it is necessary to examine empathy under hunger conditions better to understand the motivational relationship between hunger and empathy.

Study 2 was designed to potentially elucidate the behavioral, affective, and autonomic correlates of motivational competition between hunger, empathy, and pain. I first investigated any potential impact of hunger on cognitive and affective empathy, hypothesizing that hunger would be associated with dampened cognitive and affective empathy. Also, I hypothesized that hunger would be associated with decreased perception of pain in others – the second index of empathy, due to a reorientation of cognitive and emotional resources towards goals associated with food consumption. I also used a pain induction protocol to investigate the relationship between hunger and pain. I hypothesized that hungry participants would show a dampened pain response resulting from the motivational prioritization of hunger. I also predicted that

34

participants in the hunger group would demonstrate higher baseline PNS activity, indicating heightened emotional and physiological flexibility (Kok & Fredrickson, 2010). This hypothesis was based on past work in animal models demonstrating that brief fasting may increase resting PNS activity (Mager et al., 2006).

3.2 Methods

3.2.1 Participants

137 (91 female) University of Chicago undergraduate students and Chicago community members, ages 18 – 30 (mean 20.9) participated in the study (Asian/Pacific Islander = 32.1%, African American = 13.9%, Caucasian = 40.9%, Hispanic = 10.9%, Multiple Ethnicities = 2.2%). See Table 3. 1 for demographic and self-report measures breakdown between groups. Experimental groups were matched on age, gender, and ethnicity. Participants provided written informed consent and were provided monetary or course credit compensation for participation. This study was approved by the Institutional Review Board of the University of Chicago. Prior to enrollment in the study, participants were screened for a history of mental illness, including eating disorders. I also screened for fainting, diabetes, hypoglycemia, and medications that interfere with cardiac functioning.

3.2.2 Procedure

This procedure was approved by the Institutional Review Board of the University of Chicago. Participants were recruited from the University of Chicago student population and the local community. All participants were provided written informed consent and monetary or course credit compensation. Before enrollment in the study, participants were screened for a history of eating disorders, fainting, diabetes, hypoglycemia, and medications that interfere with cardiac functioning. Participants were randomly assigned to either the hunger or control groups.

Participants randomized to the hunger condition were informed that they were required to fast for a minimum of 6 hours before testing on the day of the study. I selected this deprivation period to capture the hunger state that most individuals experience as they approach their next meal (Batterink et al., 2010). Subjects were also informed that consuming water (but no caloric or caffeinated beverages) was acceptable to control for thirst as a competing motivation. To ensure fasting compliance to the best of our ability, I reminded participants of the fasting requirement the day before study participation and administered a sham salivary glucose test. Fasting time was measured by asking subjects how many hours and minutes it had been since their last meal.

Additionally, hunger was assessed using a 100-point Visual Analogue Scale ranging from 'Not at all Hungry' to 'Extremely Hungry' in a subgroup of participants. After completing the questionnaires, participants completed a series of behavioral tasks, detailed below. All behavioral tasks were administered using E-prime 2.0 (Schneider et al., 2002) and displayed on a 39" monitor facing the participant, seated 60" away. Participants first completed the pain recognition task and finished with the cold pressor task. After completing the cold pressor task, participants completed a battery of self-report questionnaires. Finally, the research assistant compensated the participant for their time and instructed them to leave the laboratory.

3.2.3 Measurement of the Parasympathetic Nervous System

A standard lead II configuration was used for obtaining the electrocardiogram (ECG). Data was collected using a BioNex two-slot mainframe (Mindware Technology, Gahanna, OH) connected to a laptop computer. Time stamping triggers were integrated into the behavioral task scripts to provide millisecond resolution for the cardiac and behavioral data. ECG was sampled at 1000 Hz. The ECG signal was analyzed using Mindware Technology's HRV software,

Version 3.10. Visual inspection and manual data editing were completed to ensure proper artifacts and ectopic heartbeat removal.

Respiratory sinus arrhythmia (RSA) is a phenomenon associated with heart rate fluctuation within the respiratory frequency band. RSA refers to the speeding and slowing of the heart via the vagus nerve, the principal nerve of the PNS. High-frequency heart rate variability (hf-HRV) (a measure of RSA) was derived by spectral analysis (Mindware HRV software, Version 3.1.5) of the interbeat interval series obtained from the ECG. The interbeat interval series was time-sampled at 4 Hz to obtain an equal interval time series that will be detrended, end-tapered and submitted to a Fast Fourier Transform, which then was integrated over the respiratory frequency band (0.12 – 0.42 Hz).

3.2.4 Measures of the Sympathetic Nervous System

Pre-ejection period (PEP) derived from impedance cardiography is the period between the electrical invasion of the ventricular myocardium (Q wave of the ECG) and the aortic valve opening. PEP depends on the time development of intraventricular pressure; it is widely used as an index of myocardial contractility. Because variations in contractility are primarily under sympathetic control, PEP is commonly used as a noninvasive measure of sympathetic cardiac control (J. T. Cacioppo et al., 1994). Lower PEP values represent higher levels of sympathetic cardiac control. PEP values are represented in milliseconds.

3.2.5 Pain Sensitivity Task

To assay empathy related to hunger, sensitivity to pain in others was measured using a previously validated pain recognition paradigm (Decety et al., 2010). This task involves viewing ten short videos of different individuals expressing pain and rating the amount of pain expressed using a Visual Analogue Scale (ranging from 'no pain' to 'very intense pain'). Higher ratings on

this scale correspond to heightened sensitivity for pain in others. The video clips are 3.5 seconds in duration. The videos showed the transition from neutral (0.5 s) to pained (3 sec) facial expression, demonstrating an acute pain stimulus-response. See Figure 3.1 for a visual representation of the pain sensitivity task.

3.2.6 Pain Tolerance Task

I chose to use the cold pressor paradigm, a widely used method in research settings, to assess pain tolerance (Mitchell et al., 2004) (Lovallo, 1975). During the cold pressor task, participants were instructed to submerge their left foot in circulating water and ice, maintained at $0 - 3 \degree$ C. Participants were instructed to hold their foot in the cold bath for as long as they could tolerate. The task ended as soon as the participant removed their foot from the bath. The maximum duration allowed was 300 seconds. If the participant still had their foot in the bath at 300 seconds, the experimenter instructed the participant to remove their foot from the bath. The participants' duration in the bath was used as the primary outcome measure of pain tolerance. Longer durations are interpreted as higher pain tolerance. Additionally, participants reported their perception of pain every 30 seconds using a Visual Analogue Scale (ranging from 'no pain' to 'the worst pain imaginable').

3.2.7 Self-Report Questionnaires

Participants completed self-report questionnaires, including the Questionnaire of Cognitive and Affective Empathy (QCAE) (Reniers et al., 2011). The QCAE contains two subscales, indexing cognitive empathy and affective empathy. Cognitive empathy can represent the internal mental state of another individual or theory of mind. Affective empathy can be described as a response to the emotional display of another person and other emotional stimuli (Reniers et al., 2011). Participants also completed the Positive and Negative Affect Schedule

(PANAS) (Watson et al., 1988a). The PANAS is one of the most commonly used measures of mood, comprised of two 10-item scales used to extract measures of positive and negative affect.

3.2.8 Data Analysis Plan

All analyses were run with and without age, gender, and ethnicity as covariates. Adding these demographic variables into models did not change model significance. The results described below are reported without demographic variables in the models. Hunger was operationalized in three ways: 1) hunger ratings measured on a 100-point Likert scale, 1) time since last meal measured in hours and minutes, and experimental grouping (hunger/control). Hunger ratings and time since last meal were measured and analyzed continuously, and experimental grouping was a factor variable in models. Models with hunger ratings only include participants who has fasted for a minimum of 6 hours. Unpaired t-tests were used to compare experimental groups' behavioral task results and questionnaire measures. Pearson correlations were used to test relationships between continuous measures. Autonomic and behavioral values +/- 3SD from the mean were excluded from analyses. Statistics were run in R (version 4.1.2). All models were generated in base R. Data cleaning and manipulation were done using the dyplyr package (Mailund, 2019). Figures were generated using the ggplot2 package (Wickham, 2011) and Microsoft Excel.

3.3 Results

3.3.2 Participant Exclusion

Of the 137 participants, eight were excluded from PNS activity analyses due to inadequate quality of baseline autonomic recording. Four subjects were excluded from the behavioral empathy analyses due to incomplete task data. Additionally, twenty-seven

participants were excluded from the cold pressor analyses due to failure to submerge their foot in the water bath or a task malfunction resulting in inaccurate behavioral data.

3.3.1 Manipulation Check

Participants in the control condition averaged 2.98 hours since the last meal ($sd = 1.49$) and reported an average of 42.51 ($sd = 29.96$) on the hunger scale. Within the hunger group, hours since the last meal varied from 6 to 21 hours, and in the control group, hours since the last meal varied from 0 to 5 hours. Within the hunger group, hunger ratings ranged from 9 to 100, and in the control group, hunger ratings ranged from 0 to 86. Both hours since last meal ($t_{61} = 11.13$, $p < 0.001$) and hunger ratings ($t_{62} = 3.74$, $p < 0.001$) were significantly different between experimental groups. Data were analyzed between experimental conditions and regressed across hours since the last meal and hunger ratings.

Across all subjects, hunger ratings positively correlated with hours since the last meal ($r(64) = 0.38$, p < 0.01), and thus I am confident that our fasting intervention induced an increase in hunger. The relationship between hunger ratings and time since last meal was particularly strong in control group ($r(39) = 0.49$, p < 0.01). Surprisingly, there was not a significant correlation between hunger ratings and time since the last meal in the hunger group ($r(23) = -0.06$, p > 0.05), demonstrating that hunger levels were relatively homogenous throughout the hunger group. Participants in the hunger condition averaged 10.51 ($sd = 4.86$) hours fasted and reported an average of 66.24 ($sd = 21.42$) on the hunger scale.

3.3.3 Self-Report Questionnaires

See Figure 3.1 for a correlation matrix of questionnaire measures collected during Study 2. See Table 3. 1 for a breakdown of demographic variables and questionnaire measures between experimental groups.

Counter to our predictions, there were no significant group differences in self-reported cognitive or affective empathy ($t_{119} = 0.13$, $p > 0.05$), ($t_{112} = 0.96$, $p > 0.05$). Also counter to our predictions, hunger ratings were not associated with either cognitive ($r(23) = 0.21$, $p > 0.05$) or affective ($r(23) = 0.18$, $p > 0.05$) empathy ratings. Additionally, time since last meal was not significantly associated with cognitive ($r(53) = 0.13$, $p > 0.05$) or affective ($r(53) = 0.10$, $p > 0.05$) empathy.

Additionally, there were no significant differences between groups in positive ($t_{117} = 0.40$, $p > 0.05$) or negative affect ($t_{119} = 0.09$, $p > 0.05$). Hunger ratings were not significantly associated with positive ($r(23) = 0.46$, $p > 0.05$) or negative affect ($r(23) = 0.16$, $p > 0.05$). Time since last meal was not significantly associated with positive ($r(53) = 0.23$, $p > 0.05$) or negative ($r(53) = 0.95$, $p > 0.05$) affect.

3.3.4 Pain Sensitivity Task

The pain sensitivity task was analyzed for the average pain rating of others (0 – 100) across ten trials. Participants reported an average of 40.0(sd = 14.8) on this scale across trials.

Results from the pain recognition task revealed no significant differences between groups ($t_{102} = 0.94$, $p > 0.05$). There was also no significant relationship between hunger ratings and pain recognition ratings ($r(23) = 0.10$, $p > 0.05$).

3.3.5 Pain Tolerance Task

Participants were allowed to keep their foot in the cold bath for a maximum of 300 seconds and averaged 200.9 (sd = 116.29) seconds in the cold bath. Latency to remove foot from the cold bath ranged from 9.5 seconds to 300 seconds. Participants' first pain rating, taken directly after placing their foot in the cold bath, averaged 25.9(sd = 18.9), on a 100 point Likert

scale. Participants' reported an average of 58.2 (sd = 20.9) for their maximal pain rating on the same 100 point Likert scale.

Latency to remove foot from the bath was non-significant between groups (t_{94} = 0.97, p > 0.05). Self-reported pain ratings between groups were not significantly different (t_{79} = 1.70, p = 0.09). There was a trending result such that individuals in the hunger group reported higher pain ratings than individuals in the control group (t_{79} = 1.70, p = 0.09). Time fasted did not significantly correlate to either latency to remove foot ($r(41)$ = 0.04, p > 0.05) or self-reported pain ratings ($r(42)$ = 0.15, p > 0.05). Hunger ratings did not correlate with either latency to remove foot ($r(19)$ = 0.27, p > 0.05) or perceived pain ratings ($r(19)$ = 0.22, p > 0.05). See Figure 3.12 for a visualization of latency to remove foot from the cold bath between experimental groups. See Figure 3.13 for a visualization of pain ratings between experimental groups.

3.3.6 Autonomic Activity

Resting hf-HRV was significantly higher in the hunger group relative to the control group (t_{118} = 2.05, p < 0.05), consistent with our prediction. See Figure 3.7 for a visualization of hf-HRV between experimental groups. Resting SNS activity, indexed by PEP, was lower, but not significantly so, in the hunger group than the control group (t_{122} = 1.72, p = 0.08). See Figure 3.9 for a visualization of this relationship. In the hunger condition, Baseline hf-HRV was not significantly correlated hunger ratings ($r(20)$ = -.09, p > 0.05). Hunger ratings in the hunger group were not significantly related to resting SNS activity (t_{20} = 0.41, p > 0.05).

SNS activity, as indexed by PEP, significantly rose during from baseline to the first minute of the cold pressor task t_{69} = 2.03, p < 0.05. While PNS activity generally dropped, there was no significant change in PNS activity from baseline to the first minute of the cold pressor

task ($t_{97} = 1.16$, $p > 0.05$).There were no significant group by time interactions between group membership (hunger/control) and SNS $F(1, 68) = 1.76$, $p > 0.05$ or PNS $F(1, 97) = 1.47$, $p > 0.05$) change from baseline to the first minute of the cold pressor task.

3.4 Discussion

The current study was designed to elucidate the behavioral, affective, and autonomic correlates of motivational competition between hunger, empathy, and pain. I first confirmed that our fasting manipulation worked by verifying that individuals assigned to fast for a minimum of 6 hours self-reported higher hunger ratings than individuals in the control group.

I predicted that participants in the hunger group would demonstrate higher baseline PNS activity, indicating heightened emotional and physiological flexibility (Kok & Fredrickson, 2010). I found a significant effect on hunger and resting PNS cardiac control. Subjects in the hunger induction group had higher baseline hf-HRV values than subjects in the control group. Higher resting PNS activity is associated with improved emotion and cognitive regulation (Smith et al., 2017). Our results demonstrating that fasting for 6+ hours is associated with heightened PNS activity indicate that brief fasting may have a positive impact on cognitive and emotional regulatory processes.

I had hypothesized that hungry participants would show diminished empathy. Results from Study 2 show that there were no significant differences between individuals in the sensitivity to the pain of others as a function of hunger motivation. Additionally, there were no significant relationships between hunger and self-reported cognitive or affective empathy. Although past work has suggested that empathy is flexible given interpersonal and contextual factors (Decety, 2015b), short-term hunger may be too mild of a stressor to influence empathy directly.

I hypothesized that hungry participants would show a dampened pain response resulting from the motivational prioritization of hunger. I saw no significant relationship between hunger and behavioral responses to pain. These data suggest that acute hunger may not influence shifts in acute pain perception. One potential explanation for this is that acute pain must be prioritized over hunger in most contexts. While hunger-induced chronic pain dampening has been previously reported (Bosley et al., 2004), additional work is needed to understand the relationship between hunger and acute pain.

Limitations of the current study include the sample used, primarily composed of undergraduates at the University of Chicago, whose results may not generalize to a broader population. Additionally, I could not guarantee that participants complied with the fasting instructions with absolute certainty. We also chose to use a somewhat limited fasting duration. Perhaps 6 hours is not a long enough fasting duration to induce motivational shifts between hunger, empathy, and pain. Taken together, our study's findings provide little evidence for direct motivational shifts within the domains of acute hunger, positive or negative empathy, pain, and empathy after acute hunger induction. Hunger is an integral component of allostatic regulation, yet many unanswered questions about how this life-sustaining motivation interacts with co-occurring motivational processes. This line of research warrants future investigation, as studies examining motivational competition during acute hunger have implications for biological, cognitive, and social processes related to food procurement and consumption. Examining hunger using a more comprehensive range of fasting durations will allow us to understand better how hunger's magnitude plays a role in dynamic motivational systems.

3.5 Appendix B: Chapter 3 Figures and Tables

(N = 137)

	Control Group	Fasting Group
Number of Subjects	82	55
Hours Fasted	$3.0_{(0.16)}$	$10.5_{(0.66)}$
Sex (% female)	65.4	69.1
Age (years)	$21.0_{(0.32)}$	$20.5_{(0.34)}$
PANAS - Negative Affect	$14.7_{(0.61)}$	$14.7_{(0.72)}$
PANAS - Positive Affect	$26.7_{(0.97)}$	$26.1_{(1.17)}$
STAI - Trait	$39.4_{(0.95)}$	$38.9_{(1.27)}$
CES-D	$12.0_{(0.89)}$	$11.3_{(1.15)}$
Cognitive Empathy Score	$36.6_{(0.90)}$	$36.8_{(1.06)}$
Affective Empathy Score	$26.5_{(0.51)}$	$27.3_{(0.67)}$

Table 3. 1 Study 3 Demographic and Self-Report Measures

Numbers in parentheses represent standard deviation.
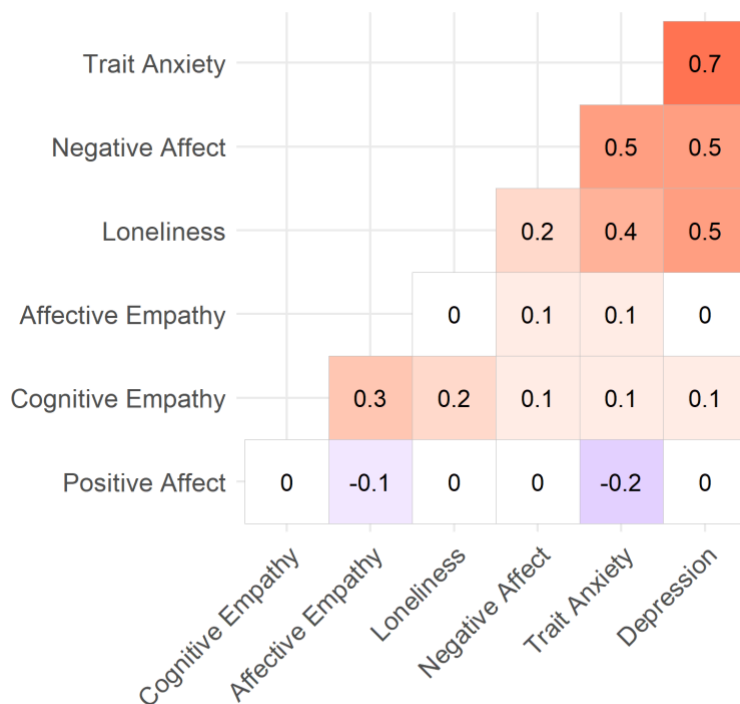
Figure 3. 1 Study 2 questionnaire correlation matrix

Numbers in boxes represent Pearson correlation coefficients.

Figure 3. 2 Example stimuli from Pain Sensitivity Task

These images represent stills from the 3-second video clips. Stimuli were borrowed with permission from (Decety et al., 2010).
Figure XX: Hunger Ratings, compared between groups
Individuals who fasted for 6+ hours (i.e., 'hunger' group) reported significantly higher hunger ratings than individuals in the control group.
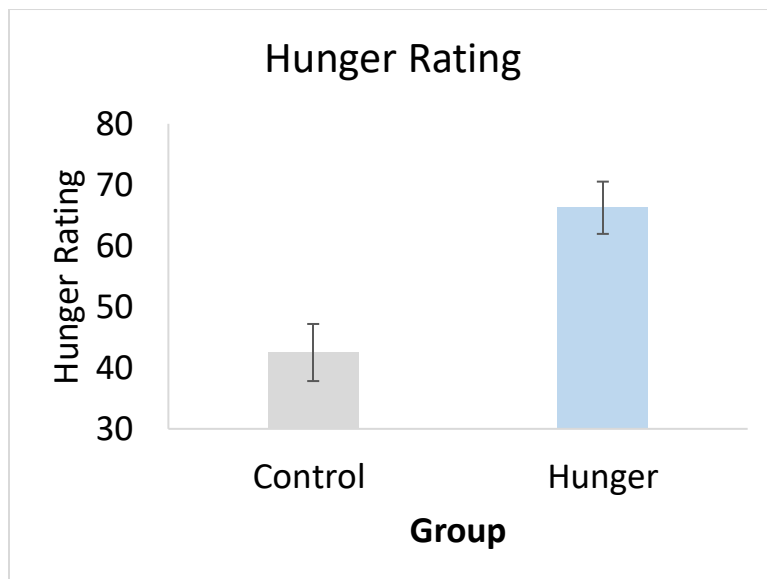
Figure 3. 3 Hunger ratings, compared between groups

Individuals in the hunger group (i.e., fasted for more than 6 hours) reported significantly higher hunger ratings than individuals in the control group ($t62 = 3.74$, $p < 0.001$). Error bars represent standard error of the mean.
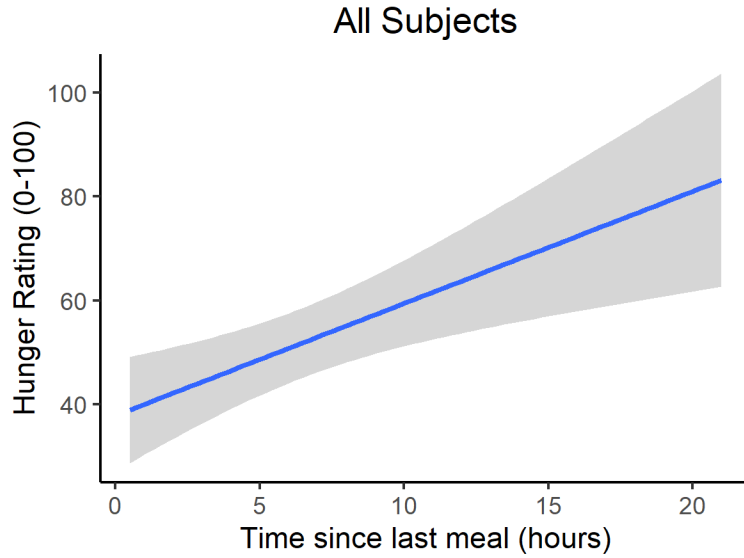
All Subjects

Figure 3. 4 Relationship between time fasted and hunger ratings across all subjects

Across all subjects, there was a positive linear relationship between hours since the last meal and hunger ratings ($r(64) = 0.38$, $p < 0.01$). The shaded grey region represents the standard error of the mean.
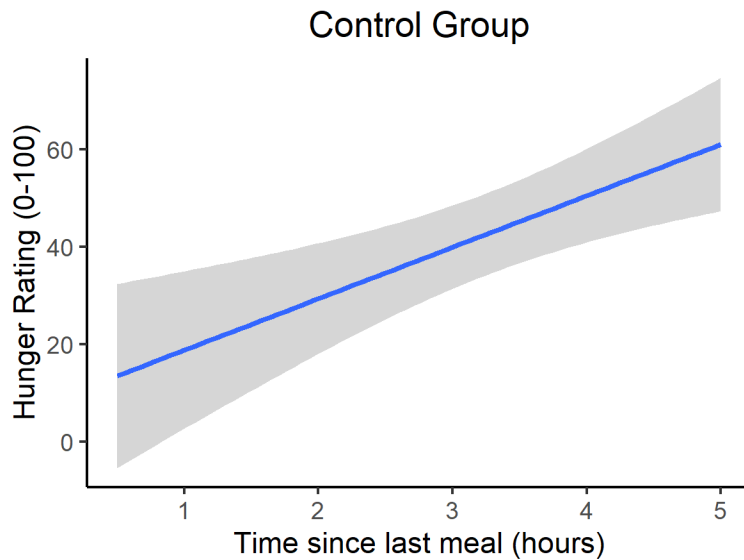
Control Group

Figure 3. 5 Relationship between time fasted and hunger ratings, control group

In the control group (hours since last meal < 6) there was a positive linear relationship between hours since last meal and hunger ratings ($r(39) = 0.49$, $p < 0.01$). The shaded grey region represents the standard error of the mean.
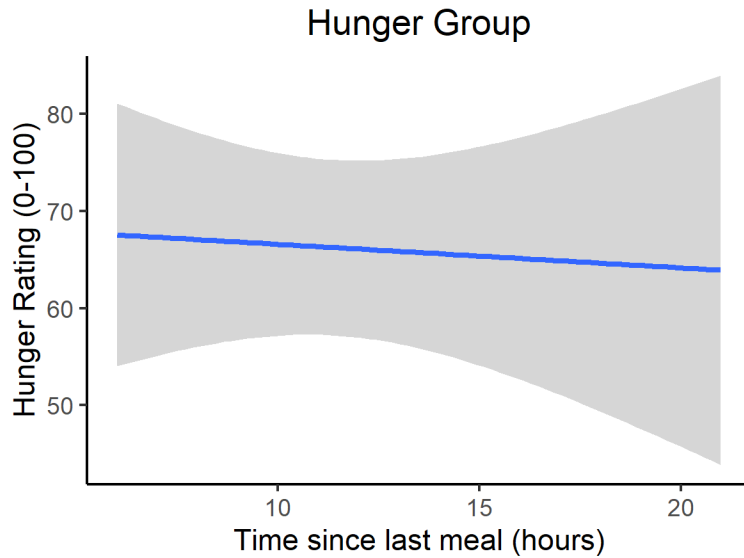
Figure 3. 6 Relationship between time fasted and hunger ratings, hunger group

There was no significant relationship between time since the last meal and hunger ratings in the hunger group (> 6 hours since the last meal). The shaded grey region represents the standard error of the mean.
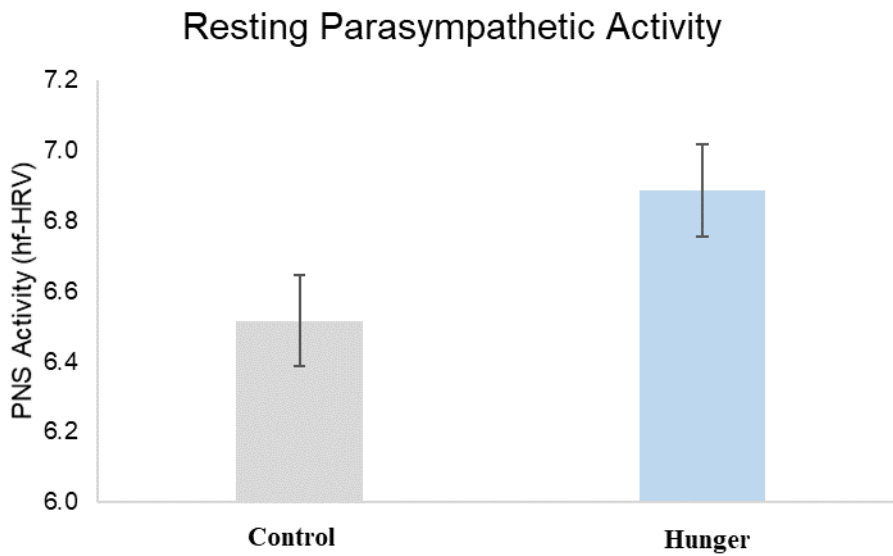
Figure 3. 7 PNS activity at rest, compared between experimental groups

Individuals in the hunger group demonstrated significantly higher PNS activity at rest than control group members ($t_{118} = 2.05$, $p < 0.05$). Error bars represent the standard error of the mean.
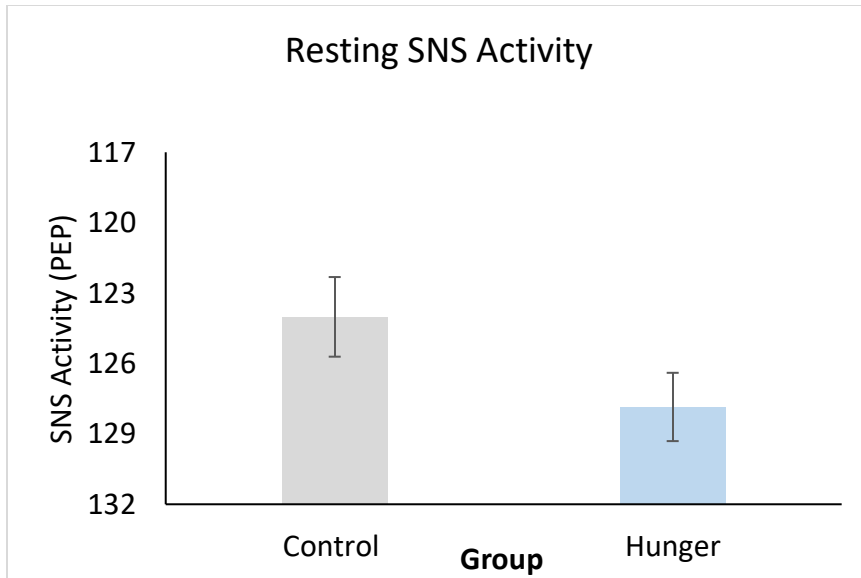
Figure 3. 8 SNS activity at rest, compared between experimental groups

Individuals in the hunger group demonstrated lower SNS activity at rest than control group members ($t_{122} = 1.72$, $p = 0.08$). Y-axis reverse scored because lower PEP values represent higher SNS activity.
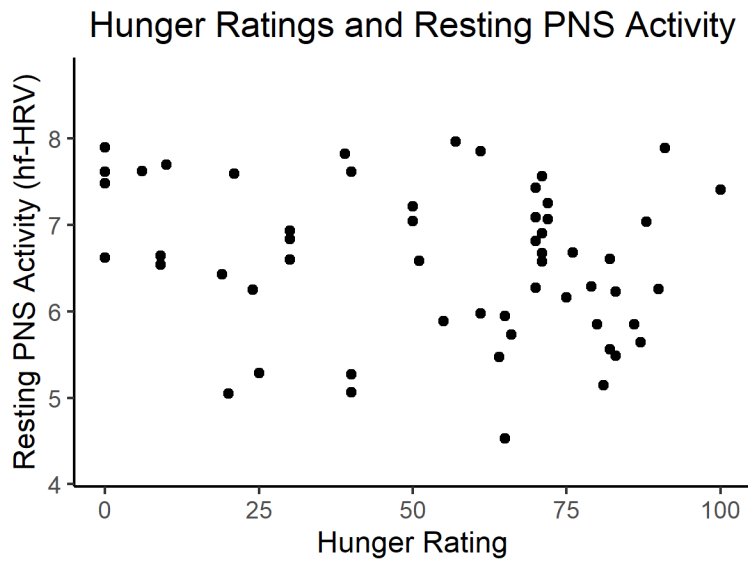
Figure 3. 9 PNS activity at rest, hunger rating

There was no significant relationship between hunger ratings and PNS activity at rest.

49

Sensitivity to Pain in Others
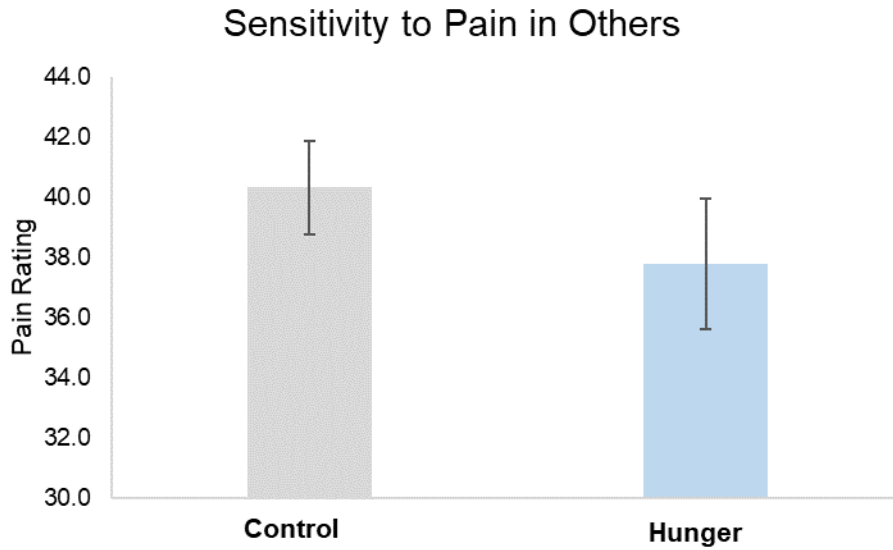
Figure 3. 10 Sensitivity to pain in others, compared between groups

There was no significant difference between experimental groups in pain sensitivity ratings for others (t_{102}= 0.94, p > 0.05). Error bars represent standard error of the mean.

Hunger Group & Self-Reported Empathy
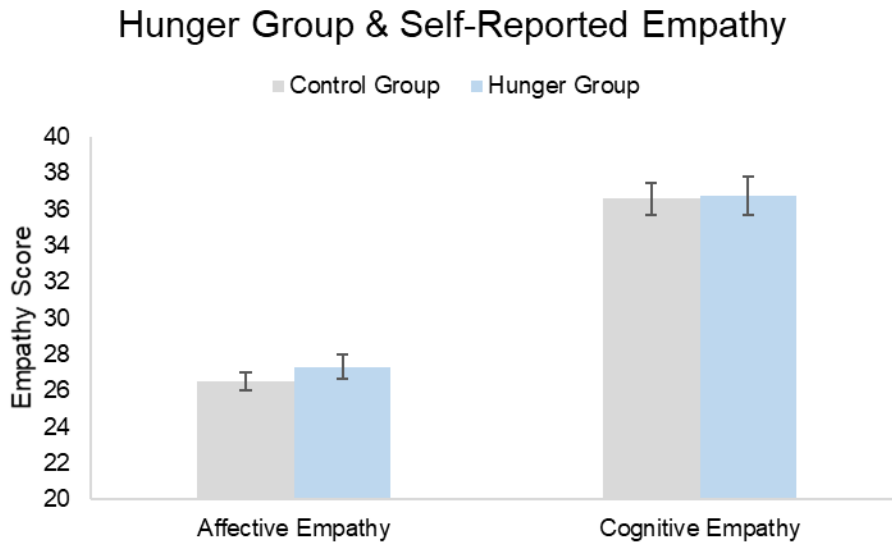
Figure 3. 11 Cognitive and affective empathy scores, compared between groups

There was no significant difference between hunger groups in self-reported cognitive empathy ($t_{119} = 0.13$, $p > 0.05$) or affective empathy ($t_{112} = 0.96$, $p > 0.05$). Error bars represent the standard error of the mean.
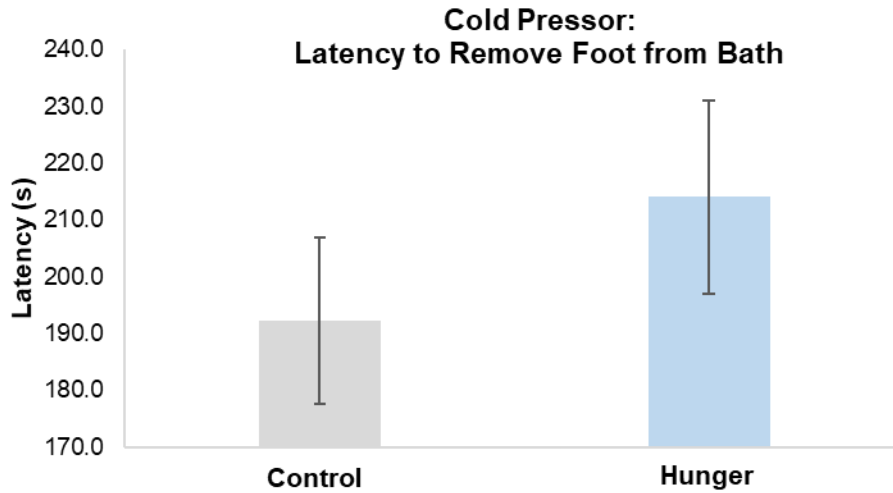
Figure 3. 12 Time to remove foot from cold bath, between groups

There was no significant difference between hunger groups in how long participants kept their feet in the cold bath ($t_{94} = 0.97$, $p > 0.05$). Error bars represent the standard error of the mean.
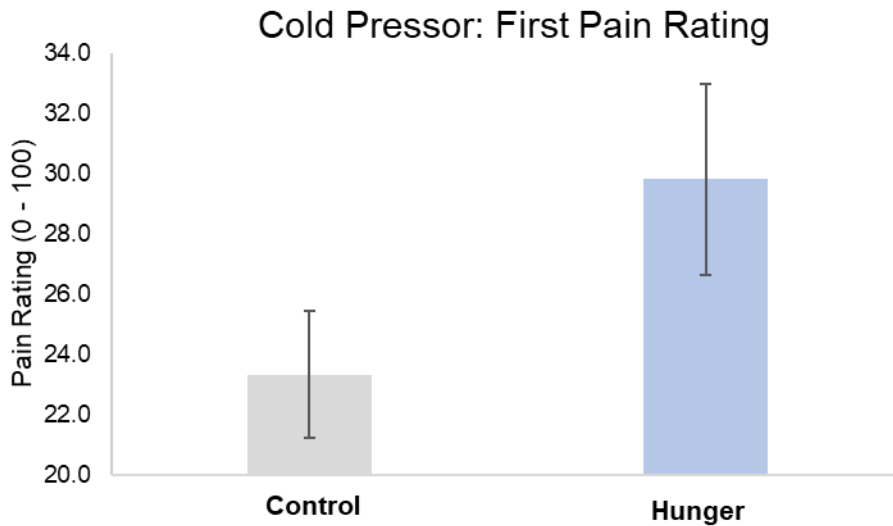
Figure 3. 13 Cold Pressor: first pain rating, between groups

Individuals in the hunger group demonstrated higher first pain ratings than individuals in the control group. While not statistically significant, the result was trending ($t_{79} = 1.70$, $p = 0.09$). Error bars represent the standard error of the mean.
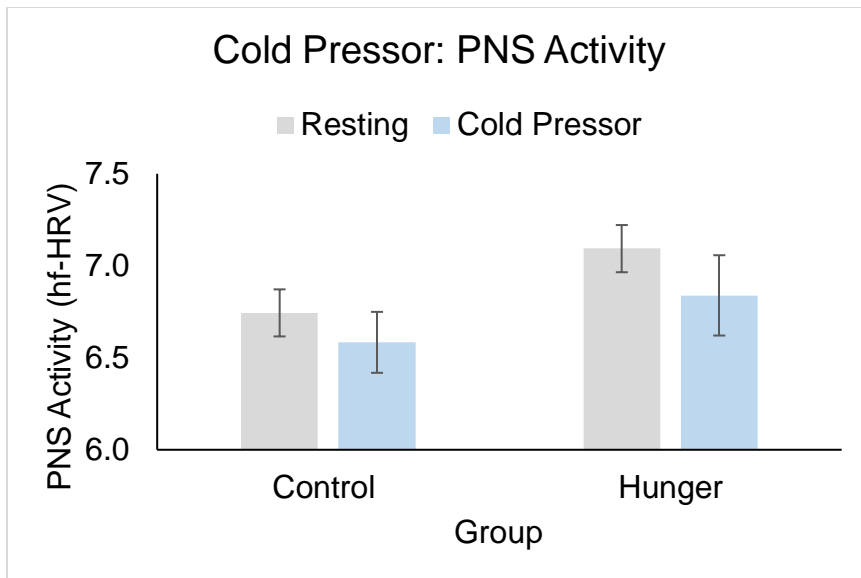
Figure 3. 14 Cold Pressor: PNS Activity

There was no group x time interaction between experimental group (hunger/control), time (resting/cold pressor), and PNS activity $F(1, 97) = 1.47$, $p > 0.05$). Error bars represent standard error of the mean.
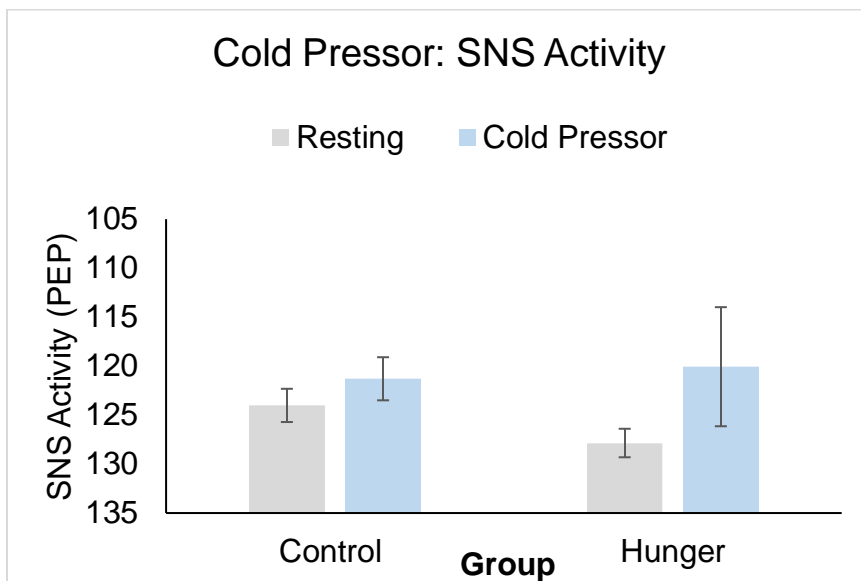
Figure 3. 15 Cold Pressor: SNS Activity

Y-axis reverse scored because lower PEP values represent higher SNS activity. There was no group x time interaction between experimental group (hunger/control), time (resting/cold pressor), and SNS activity $F(1, 68) = 1.76$, $p > 0.05$). Error bars represent standard error of the mean.

CHAPTER 4: LONELINESS AND MOTIVATED COGNITION

4.1 Introduction

The motivation to form and maintain meaningful relationships is extremely powerful because we cannot survive alone (J. T. Cacioppo & Hawkley, 2009a). Social species ranging from flies to humans benefit from relationships with conspecifics (Le Bras, 2021; Seeman, 1996). Benefits of belonging to a social group include division of labor, protection against predators, and emotional support. While the need to engage with conspecifics is ubiquitous across social species, the magnitude of this need varies across and within individuals. Some individuals require little social interaction to thrive, while others require more social engagement. Loneliness represents the pain of feeling alone during perceived social isolation (J. T. Cacioppo & Hawkley, 2009a). The perception of social isolation is what drives loneliness. Individuals can live relatively solitary lives and not experience loneliness, while other individuals who have rich social lives may feel very lonely (Hawkley & Cacioppo, 2010). Indeed, it is the perception of social isolation that drives aversive feelings associated with loneliness. Perceived social isolation predicts physical and mental health outcomes above and beyond what is predicted by objective social isolation. For example, perceived social isolation predicts elevated blood pressure beyond what could be predicted by social support or objective social isolation (Hawkley et al., 2006). Additionally, perceived social isolation has been found to predict lifetime depressive symptomatology above and beyond objective measures of isolation (J. T. Cacioppo et al., 2006)

While loneliness is certainly aversive, loneliness may have evolved to signal that one's social connections are weakened and motivate the reconnection with others needed for personal wellbeing and survival of one's genes. Much like hunger and fatigue, loneliness is highly

53

motivating and prompts behavioral shifts that enable an individual to renew life-sustaining social connections. Loneliness has been described as 'hunger' for social reconnection and the motivational components of loneliness parallel how hunger motivates us towards food procurement and consumption. Indeed, the ventral striatum, previously shown to increase in response to craving food, also activates when individuals view images of close loved ones (Inagaki et al., 2016). Following brief bouts of loneliness, individuals often successfully diminish feelings of social isolation and meet their social goals (Matthews-Ewald & Zullig, 2013). Previously lonely individuals are able to diminish feelings of social isolation because they have reached their goal. In this instance, the motivation to reengage with the social world prevailed and these previously lonely individuals now feel more secure in their social relationships.

However, approximately 20-30% of individuals report chronic loneliness (Martín-María et al., 2020). It is often deleterious to one's physical and mental health to be lonely for prolonged periods of time. While acute loneliness is highly motivating, chronic loneliness may no longer aid in social re-connection and can often be hazardous to an individual's physical and mental health. Chronic loneliness is highly aversive and may lead individuals to believe that their social goals are impossible, potentially leading to a series of behavioral confirmation processes and negative social interactions. Not only does time spent away from conspecifics leave an individual vulnerable to environmental threats, but actual and perceived social isolation is also associated with a gambit of severe health outcomes (Cacioppo et al., 2002). A growing body of literature has documented the association between loneliness and cardiac, endocrine, and immune dysregulation (J. T. Cacioppo et al., 2002; S. J. Wilson et al., 2019), ultimately leading to higher morbidity and mortality rates in lonely individuals.

When the relationship between loneliness and adverse health outcomes was first examined, researchers developed the social control hypothesis as a possible mechanistic explanation for the relationship between loneliness and mortality (Umberson, 1992). Social control theory holds that the influence of social connections tends to discourage poor health behaviors and encourage good health behaviors. However, this explanation does not provide a sufficient mechanistic explanation for isolation's deleterious mental and physical effects. For example, objective social isolation is associated with decreased lifespan in ants (Koto et al., 2015) and adiposity in mice independent of food intake (Sun et al., 2014).

Chronic loneliness is also associated with aversive psychological outcomes. Chronic loneliness is broadly associated with weakened cognitive functioning (O'luanaigh et al., 2012): inclusive of acceleration of cognitive decline and risk for Alzheimer's Disease (Wilson et al., 2007), increased negativity and depressive cognition (Donovan et al., 2017), and heightened sensitivity to social threats (Nowland et al., 2018). Cacioppo's loneliness and social cognition model (J. T. Cacioppo & Hawkley, 2009b) asserts that loneliness contributes to biased social cognition and self-defeating cognitive psychophysiological processes. The biases in social cognition may be one mechanism through which loneliness may lead to adverse health outcomes (Hawkley & Cacioppo, 2010). Shifts in cognition associated with loneliness impact emotions, decisions, behaviors, and interpersonal interactions, contributing to the association between loneliness and morbidity (J. T. Cacioppo & Hawkley, 2009b).

The capacity to control attention is a crucial component of executive functioning and corresponds with an individual's ability to meet social standards and personal goals. (Diamond, 2013). Several recent studies have documented attentional shifts associated with loneliness. For example, lonely individuals more rapidly differentiate between negative social stimuli and

negative non-social stimuli (S. Cacioppo et al., 2015), indicating an attentional bias towards

negative environmental cues. These findings suggest that loneliness is associated with a

heightened saliency of negative social information. In the short-term, hypersensitivity to social

cues is adaptive for individuals aiming to reengage with group members. Attending to social

cues allows lonely individuals to direct psychophysiological resources toward meeting their

social goals. However, if left unchecked, hypersensitivity to negative social information may

adversely shape social expectations and contribute to psychological and health outcomes

associated with chronic loneliness.

Much like attention, working memory is an integral component of adaptive psychological

functioning (Salminen et al., 2012). While not as yet studied as loneliness and attention, some

evidence suggests that loneliness may positively impact working memory. For example,

depressed individuals experiencing high levels of loneliness have performed more accurately on

working memory tasks when compared to non-lonely depressed individuals (Gao et al., 2020),

reinforcing the theory that brief bouts of loneliness may positively impact cognition that aids in

reengagement with the social world. Lonely individuals also demonstrated more robust

functional connectivity between the cognitive control network and the dorsomedial prefrontal

cortex during working memory performance. These neuroimaging results may be due to lonely

individuals' greater negative self and social cognitive bias (J. T. Cacioppo & Cacioppo, 2018),

indicating that lonely individuals require greater regulatory effort while performing cognitive

tasks. To the best of our knowledge, there is no literature directly examining loneliness and

working memory capacity in a non-clinical or non-geriatric population.

The current study aims to provide insight into the effects of loneliness across multiple

cognitive domains, including attention and working memory. I chose to use a loneliness

induction paradigm induced to induce feelings of acute loneliness. My chosen loneliness

induction method was randomly assigning individuals to receive messages indicating that they

are likely to end up alone in life or lead rich social lives. This paradigm has been used

extensively in the loneliness literature and has been demonstrated to produce shifts in cognitive

performance (R. Baumeister et al., 2002) and has been successful in inducing feelings of

loneliness, based on the perception that one may end up alone (J. T. Cacioppo et al., 2014). I

sought first to replicate the well-documented shifts in attention associated with loneliness (J. T.

Cacioppo et al., 2014). I predicted that lonely individuals would shift attentional resources

towards negative words (both social and non-social), as measured by administering a Social and

Emotion Stroop task. This prediction is based on past work demonstrating a cognitive negativity

bias associated with loneliness (Montoliu et al., 2019). Additionally, I intended to replicate past

work demonstrating that negative social stimuli are differentiated from negative nonsocial

stimuli more rapidly in the lonely than in nonlonely individuals (S. Cacioppo et al., 2015). Next,

I examined any impact loneliness may have on working memory capacity with the prediction

that lonely individuals will demonstrate working memory capacity deficits based on well-

documented cognitive deficits associated with loneliness (J. T. Cacioppo & Cacioppo, 2014).

4.2 Methods

4.2.1 Participants

Participants were recruited from Amazon Mechanical TURK. Participants with US IP

addresses and a task approval rate above 95% were allowed to participate. Additionally,

participants were screened for color blindness prior to enrollment. Participants provided

informed consent prior to enrolling in the study and each Human Intelligence Task (HIT) was

compensated at $6/hour. 99 participants (46 female), 21 – 73 years old (mean 39.0, sd = 11.5)

participated in the study. The sample's ethnicity breakdown was as follows: Asian/Asian American = 8.2%, Caucasian = 71.0%, African American = 11.0%, Hispanic = 6.2%, Multiple Ethnicities = 3.1%. The sample's educational attainment breakdown was as follows: Some High School = 1.0%, High School Diploma = 35.1%, Trade School = 7.2%, Undergraduate Degree = 46.4%, Master's Degree = 9.3%, Doctoral Degree = 1.0%. The Future Alone and Future Belong groups did not significantly differ in age ($t_{95} = 0.13$, $p > 0.05$), gender ($X^2(1, N = 97) = 1.21$, $p > 0.05$), race ($X^2(4, N = 97) = 1.07$, $p > 0.05$), or educational attainment ($X^2(5, N = 97) = 2.19$, $p > 0.05$). See Table 4. 1 for a breakdown of self-report and demographic measures between experimental groups.

4.2.2 Procedure

This procedure was approved by the Institutional Review Board at the University of Chicago and was housed on Amazon Mechanical TURK (MTURK) and PsyToolKit's servers. Participants completed the study in an average of 37.7 (SD = 8.9) minutes. Participants enrolled in the study on MTURK were linked to a series of self-report questionnaires and behavioral tasks housed on PsyToolKit. First, participants completed the self-report questionnaires. After completing the questionnaires, participants engaged in a future loneliness manipulation described below. Participants completed a series of behavioral tasks following the future loneliness manipulation described below. Finally, participants were debriefed through an on-screen message that communicated the purpose of the study.

4.2.4 Future Loneliness Manipulation

I used a social anticipation paradigm to manipulate participants' perceptions of social isolation. Participants were randomly assigned to receive one of two messages after completing the self-report questionnaires. Participants were led to anticipate either a future filled with

satisfying relationships (Future Belong) or a lonely life (Future Alone), allegedly based on their questionnaire ratings.

The Future Alone message read as follows: 'Based on the results from the questionnaires you just completed: You are the type of person who will end up alone later in life. You may have several relationships, but these are likely to be short-lived. Relationships do not last, and when you are past the age where people are constantly forming new relationships, the odds are you'll end up being alone more and more.'

The Future Belong message read as follows: 'Based on the results from the questionnaires you just completed: You are the type who has rewarding relationships throughout life. You are likely to have a long and stable relationship and have friendships that will last into your later years. The odds are that you'll always have friends and people who care about you'.

This paradigm was initially developed by (J. Twenge et al., 2002). Since then, this manipulation has been recognized as an accurate method of inducing an impression of future social isolation (Wirth, 2016).

After reading either the Future Belong or the Future Alone message, participants were asked 'How accurate do you think the prior statement was about your future?' and responded to this question using a 5-point Likert scale ranging from 'Not at All' to 'Extremely'. Additionally, participants completed a 3-item abbreviated version of the UCLA Loneliness Scale (Hughes et al., 2004) to assess momentary loneliness directly following the anticipation paradigm.

4.2.3 Self-Report Questionnaires

Participants completed a battery of self-report questionnaires to satisfaction with life satisfaction with social relationships, personality, and affect. Questionnaire measures included the UCLA Loneliness Scale (Version 3) (Russell, 1996), the Perceived Stress Scale (Cohen,

n.d.), the Center for Epidemiological Studies Depression Scale (CES-D) (Radolf, 1977), the

Positive and Negative Affect Schedule (Watson et al., 1988b), The Satisfaction with Life Scale

(Diener et al., 1985), and the Questionnaire of Cognitive and Affective Empathy (Reniers et al.,

2011).

After the future loneliness manipulation, I administered a 3-item version of the UCLA

Loneliness Scale. I assessed mental fatigue at baseline and after each block of the behavioral

tasks using a 5-point Likert scale ranging from 'Not at All' to 'Extremely'. I also asked

participants how bored, content, irritable, and interested they were, using the same 5-point Likert

scale between each experimental block to mask that I was interested in assessing mental fatigue

at these time points.

4.2.4 Behavioral Tasks

All behavioral tasks were administered online via PsyToolKit (Stoet, 2010, 2017), a

stimulus presentation software that has been validated against E-Prime 3.0 for accuracy of both

response choice and response time (Kim et al., 2019). Behavioral tasks were counterbalanced

such that half of the participants completed the Stroop task first, and half of the participants

completed the change detection task first.

Social and Emotional Stroop Tasks:

I administered a modified version of the classical Stroop task to assess the impact of

loneliness on attentional biases and processing speed (Ray, 1979). Participants were asked to

identify the color of social words, emotional words, and neutral words. The social and emotional

Stroop tasks are analogs of the original task that examines attentional change. Emotional and

social Stroop tasks examine attentional shifts toward affective and social word stimuli by

requiring individuals to identify the color in which emotional and social words are presented

(Holle et al., 1997; J. M. G. Williams et al., 1996). The emotional and social words were previously validated on Amazon's Mechanical Turk for use with the Stroop task (Faig, 2019). The Stroop task consisted of 5 blocks (Social Negative, Social Positive, Emotional Negative, Emotional Positive, Neutral). Each block consisted of forty trials. See Words were presented for a maximum of 2000 ms. Participants were instructed to press the 'R' key if the word was presented in red, the 'G' key if the word was presented in green, 'B' if the word was presented in blue, and 'Y' if the word was presented in yellow. See Table 4. 2 for a complete list of words used in the Stroop task.

Working Memory Task:

I administered a change detection task to assess any relationship between loneliness and working memory. The change detection task is one of the most commonly used working memory paradigms (Large et al., 2008; Rouder et al., 2011; Xu et al., 2018). Change detection measures of visual working memory have gained popularity in assessing individual differences in capacity. In the task I used, participants briefly viewed an array of simple visual items (for 200 ms), such as colored squares, and remembered these items across a short delay (1000 ms). At test, participations are presented with an item at one of the remembered locations, and they indicated whether the presented test item is the same as the remembered item ("no-change" trial) or is different ("change" trial). Participants were given 2500 ms to press either the 'Z' key for "no-change" trials or the M key for "change" trials.

The working memory paradigm consisted of 4 blocks, each with thirty trials. I chose to use a set size of 6 on all trials, based on recommendations from (Xu et al., 2018). Seventy percent were "change" trials, and 30% were "no-change" trials. Two blocks consisted of the presentation of social images. I chose to use neutral faces for the two social blocks, sourced from

The NimStim set of facial expressions (Tottenham et al., 2009). The neutral faces varied on two dimensions: sex (Male, Female) and race (White, Hispanic, Black, Asian). The remaining two blocks consisted of the presentation of neutral images. I used colored cubes for the neutral blocks. The cubes varied in two dimensions: cube color (Red, Green, Blue, Yellow) and which side of the cube had a white face (Top, Side). See Figure 4. 8 for example non-social stimuli generated for this experiment. See Figure 4. 9 for example social stimuli.

In working memory capacity estimates, performance for change and no-change trials is calculated separately as hits (the proportion of correct change trials) and false alarms (the proportion of incorrect no-change trials) and converted into a set-size-dependent score henceforth referred to as K-Score. K-Scores used in this set of analyses were calculated as follows (Xu et al., 2018):

$$K = N \text{ x } (H\text{-}FA)$$

Where N = Set Size (6 across all trials for our study), H = Hit Rate (% correct for change trials), FA = False Alarm Rate (% incorrect for non-change trials).

4.2.6 Data Analysis Plan

Our primary outcome measures of loneliness in this study are experimental grouping and baseline loneliness. Experimental grouping (Future Alone/Future Belong) was included as a fixed factor in models. As indexed by UCLA Loneliness-V3, baseline loneliness was included as a random factor in models. All analyses were run with and without age, gender, and ethnicity as covariates. Statistics were run in R (version 4.1.2). Multi-level models were run using the lme4 package (Bates et al., 2007). All predictors in regression models were standardized using the scale function in base R. All other models (e.g., ANOVA) were generated in base R. Subjects were included as a random factor in all repeated measure MLMs. Reaction time and K-Score

were dependent variables, operationalizing attentional biases and working memory capacity. Word category (Emotional/Social/Neutral) and image category (Social/Non-Social) were fixed factors in models. Visualizations were generated using the ggplot2 package (Whelan, 2008) and Microsoft Excel. Data cleaning and manipulation were done using the dyplyr package (Mailund, 2019). Reaction time (RT) was log-transformed for analyses to reduce the effects of any outliers and or skew (Whelan, 2008). Reaction time and K-Score outliers defined as +/- 3SD from the mean were excluded from analyses.

4.3 Results

4.3.1 Participant Exclusion

Two participants were excluded from the final dataset for responding incorrectly to validity checks included in the self-report questionnaires. Two subjects were excluded from the working memory task analyses for responding more than three standard deviations below or above the group mean reaction time. One subject was excluded from the Stroop task analyses due to their response accuracy falling more than three standard deviations lower than the group mean.

4.3.2 Loneliness Induction

Perceived accuracy of the questionnaire feedback was rated on a 5 point Likert scale. Individuals in the Future Alone group averaged 2.08 (sd = 1.22) and individuals in the Future Belong group averaged 3.36 (sd = 1.21) on the perceived accuracy question. Participants in the Future Alone group rated the feedback received as less accurate than participants in the Future Belong group ($t_{95} = 5.19$, $p < 0.001$). This is in line with past work using this anticipation paradigm (R. F. Baumeister et al., 2005; Piejka et al., 2021).

4.3.3 Self-Report Questionnaires

See Figure 4. 1 for a correlation matrix displaying the relationships between all self-report questionnaires. See Table 4. 1 for a breakdown of demographic and self-report measures compared between experimental groups.

Participants averaged 35.3(sd = 6.2) on the UCLA loneliness questionnaire, my chosen measure of baseline loneliness. Baseline loneliness was significantly positively correlated with depression ($r(95) = .29$, $p = 0.005$), and perceived stress ($r(95) = .31$, $p = 0.002$). Baseline loneliness was significantly negatively correlated with life satisfaction ($r(95) = -0.21$, $p = 0.03$). Depression (CES-D), perceived stress (PSS), state affect (PANAS), life satisfaction (SWLS), and cognitive and affective empathy were not predictive of either Stroop or change detection task performance.

The Future Alone and Future Belong groups were matched in baseline loneliness ($t_{91} = 0.60$, $p > 0.05$), perceived stress ($t_{81} = 0.24$, $p > 0.05$), depression ($t_{91} = 0.76$, $p > 0.05$), negative affect ($t_{92} = 1.61$, $p = 0.11$), extraversion ($t_{92} = 0.15$, $p > 0.05$), general life satisfaction ($t_{94} = 0.04$, $p > 0.05$), and cognitive ($t_{95} = 1.40$, $p > 0.05$) and affective ($t_{93} = 0.003$, $p > 0.05$) empathy. The Future Belong group had significantly higher positive affect ratings than the Future Alone group at baseline (prior to the anticipation paradigm), ($t_{95} = 2.75$, $p < 0.01$). All models comparing the Future Belong and Future Alone groups described henceforth were corrected for group differences in baseline positive affect.

4.3.4 Emotional and Social Stroop Task

Participants averaged 717.2 ms (sd = 124.1) RT across all blocks, consistent with past use of the emotional Stroop task (Ballesteros et al., 2000; S. Cacioppo et al., 2015; J. M. G. Williams et al., 1996).

There was a trending relationship between word category (Social, Emotional, Neutral) and reaction time, such that participants responded more rapidly to social words than emotional or neutral words ($\beta(97, 485) = -0.04$, SE $= 0.02$, CI $= [-0.06, -0.02]$, $p = 0.06$). See Figure 4. 4 for a visualization of Stroop RT compared between word categories across all subjects. See Figure 4. 5 for a visualization of Stroop RT compared between word category and valence across all subjects. This trending finding was driven by participants responding more rapidly to positive social words than positive emotional words ($\beta(97, 194) = 0.09$, SE $= 0.03$, CI $= [0.06, 0.12]$, $p > 0.05$). There was no significant difference in participant RT to social negative compared to emotional negative words ($\beta(97, 194) = 0.01$, SE $= 0.03$, CI $= [-0.02, 0.04]$, $p > 0.05$).

An MLM demonstrated no main effect of experimental group (Future Alone, Future Belong) on Stroop RT ($\beta(97, 485) = 0.08$, SE $= 0.09$, CI $= [-0.01, 0.17]$, $p > 0.05$). See Figure 4. 2 for a visualization of Stroop RT compared experimental grouping and collapsed across all word categories. Additionally, a 2 x 3 repeated-measure ANOVA demonstrated no significant interaction between experimental grouping and word category (social, emotional, and neutral) on RT ($F(2,384) = 0.94$, $p > 0.05$). See Figure 4. 6 for a visualization of Stroop RT between word categories and experimental grouping. There was also no significant interaction between experimental grouping, word valence (positive/negative) in predicting RT ($F(2,384) = 0.94$, $p > 0.05$). Additionally, was no difference in RT when comparing social negative and emotional negative word responses between experimental groups ($F(1,95) = 0.11$, $p > 0.05$). There was also no difference in RT when comparing social positive and emotional positive word responses between groups ($F(1,95) = 1.08$, $p > 0.05$).

An MLM demonstrated no main effect of baseline loneliness on Stroop RT, as measured by the UCLA Loneliness Questionnaire – V3 ($\beta(97, 485) = 0.08$, SE $= 0.09$, CI $= [-0.01, 0.17)$, p

> 0.05). See Figure 4. 3 for a visualization of Stroop RT compared across UCLA loneliness values, collapsed across word categories. Additionally, baseline loneliness was not predictive of any differences in RT between word categories (Social/Emotional/Neutral) ($\beta(97, 485) = 0.07$, SE = 0.1, CI = [-0.03, 1.7], p > 0.05). See Figure 4. 7 for a visualization of baseline loneliness and RT compared between Stroop word categories. Baseline loneliness was also not predictive of any differences in RT between positive and negative words ($\beta(97, 485) = 0.14$, SE = 0.1, CI = [0.04, 0.24], p > 0.05). Additionally, baseline loneliness ratings were not predictive of any differences in RT between positive social and positive emotional words ($\beta(97, 194) = 0.07$, SE = 1.0, CI = [-0.03, 0.17], p > 0.05). Baseline loneliness ratings were also not predictive of any differences in RT between negative social and negative emotional words ($\beta(97, 194) = 0.06$, SE = 0.1, CI = [-0.04, 0.16], p > 0.05).

4.3.5 Change Detection Task

K-Score was our primary outcome measure of working memory capacity derived from the change detection task described above. K-Score values ranged from -0.69 to 3.70, with an average of 1.43(sd = 1.04). These K-values are consistent with past work using visual working memory paradigms (Rouder et al., 2011; Xu et al., 2018).

A repeated-measures ANOVA revealed that participants demonstrated stronger working memory capacity on non-social blocks compared to social blocks ($F(1,95) = 4.58$, p < 0.05). See Figure 4. 12 for a comparison of social vs. non-social working memory performance, collapsed across all participants.

A repeated measure ANOVA demonstrated no relationship between experimental group membership and K-Score, analyzed across all blocks ($F(1,94) = 0.43$, p > 0.05). See Figure 4. 10 for visualization of working memory performance compared between experimental groups

collapsed across image categories. Additionally, there were no experimental group differences when comparing K-Scores between social and non-social blocks ($F(1,94) = 0.94$, $p > 0.05$). Figure 4. 13 for a visualization of working memory performance broken down by image category and experimental grouping. There was no significant relationship between baseline loneliness ratings and K-Scores, analyzed across all blocks ($\beta(96, 192) = -0.11$, $SE = 0.09$, $CI = [-0.20, -0.02]$, $p < 0.05$). See Figure 4. 11 for visualization of working memory performance and baseline loneliness values, collapsed across image categories. Additionally, baseline loneliness was not predictive of differences in working memory capacity between image categories ($\beta(96, 192) = -0.14$, $SE = 0.10$, $CI = [-0.24, -0.04]$). See Figure 4. 14 for visualization of working memory performance and baseline loneliness, broken down by image category.

4.4 Discussion

The current study was designed to replicate and extend upon literature examining the relationship between loneliness and cognitive functioning. Past work has shown that loneliness is associated with a broad range of cognitive impairments (O'luanaigh et al., 2012), such as hypersensitivity to social threats (Nowland et al., 2018) and depressive cognition (Donovan et al., 2017). While not as thoroughly investigated as other aspects of cognition, some evidence suggests that acute loneliness may improve working memory capacity (Gao et al., 2020). Through the administration of an online study, I investigated if shifts in social motivation associated with loneliness may impact attentional biases and working memory capacity. While the relationship between loneliness and cognition has been previously examined, past work lacks behavioral support and focuses almost entirely on older adults. Counter to conventional thought; loneliness does not discriminate by age. Many children and young adults perceive themselves as socially isolated (Eccles & Qualter, 2021), particularly during the COVID-19 pandemic when

this online study was administered (Cooper et al., 2021). Extending upon current research

examining loneliness and cognition, I intentionally recruited a broad range of ages, administered

a social anticipation paradigm, and administered multiple behavioral tasks to assay attentional

biases and working memory capacity.

I operationalized loneliness through a baseline self-report questionnaire, the UCLA

Loneliness Scale-V3, and through the use of social anticipation paradigm. I used the anticipation

paradigm to manipulate participants' perceptions of future social isolation. Half of the

participants received a message that, based on their questionnaire results, they are predicted to

have a lonely future, and half of the participants received a message that they were predicted to

have a rich social life in the future. Past research using this experimental paradigm has

demonstrated that the prospect of a lonely future can cause a decrease in self-regulatory capacity

(R. F. Baumeister et al., 2005) and prosocial behavior (J. M. Twenge et al., 2007) and attentional

capacity (R. F. Baumeister et al., 2005). When asked to identify what the purpose of the study

was, none of the participants mentioned the anticipation paradigm. To the best of our knowledge,

there is no published work using this paradigm in an online setting. It is possible that the

paradigm is less efficacious when administered online compared to the traditional in-lab

administration.

Based on previous work examining loneliness and attentional biases, I hypothesized that

loneliness would be associated with attentional biases towards negative and social stimuli (S.

Cacioppo et al., 2015). I administered a social and emotional Stroop task and used RT as the

primary outcome measure of attentional bias. I did not find any main effects of baseline

loneliness on overall RT, RT compared between word categories (Social/Emotional/Neutral),

and RT compared between word valences (Positive/Negative). I also did not find any main

effects of the anticipation paradigm on overall RT, RT compared between word categories (Social/Emotional/Neutral), and RT compared between word valences (Positive/Negative). I believe that these null findings may be due to two possible reasons. First, the evidence from (S. Cacioppo et al., 2015) that suggests lonely individuals process social stimuli more rapidly than non-social stimuli is based on EEG microstates, not behavioral results. Perhaps the relationship between loneliness and attentional biases using the Social Stroop task is not identifiable at a behavioral level of analysis. Secondly, subjects in the (S. Cacioppo et al., 2015) study participated in an in-lab study wearing an EEG cap. This environmental context is highly different from our experiment hosted online and may also account for variations in results.

Based on the limited past work examining loneliness and working memory capacity, I hypothesized that loneliness would be associated with increased working memory capacity, particularly for social stimuli. This is based on past work with depressed individuals that demonstrated a positive relationship between loneliness and performance on an n-back task (Gao et al., 2020). To the best of our knowledge, there is no published work examining working memory and loneliness in healthy younger adults. I did not see any effect of loneliness on either social or non-social working memory capacity. While this result was counter to our predictions, this result suggests that loneliness in healthy adults may not impact working memory capacity. Perhaps working memory is only impacted when loneliness is chronic or coincides with clinical levels of depression.

Study 3 demonstrates that loneliness may not affect attention or working memory capacity in healthy adults. A limitation of the study was that it was conducted online, and there was not a wide range of loneliness values in the sample. Additionally, the anticipation paradigm may not induce feelings of social isolation when administered online. Future iterations of this

work conducted online should further consider the methodological constraints of manipulating loneliness in an online setting. Future work investigating the relationship between loneliness and cognition should be examined in healthy young adults. Longitudinal work examining changes in loneliness and cognitive functioning over the lifetime is necessary to understand if there is a developmental component to loneliness' impact on cognition.

4.5 Appendix C: Chapter 4 Figures and Tables

N = 97

	Future Alone (n = 50)	**Future Belong** (n = 47)
Sex (% female)	40.0	53.2
Age (years)	$40.2_{(12.0)}$	$40.5_{(11.1)}$
Ethnicity		
Caucasian	70.0	72.3
Black	14.0	8.5
Asian/Asian American	8.0	8.5
Hispanic	6.0	6.4
Multiple ethnicities	2.0	4.3
Baseline Loneliness	$34.9_{(7.0)}$	$35.7_{(5.2)}$
Life Satisfaction	$19.9_{(8.1)}$	$19.9_{(8.5)}$
Positive Affect	$19.7_{(4.9)}$	$22.4_{(4.7)}$
Negative Affect	$19.1_{(4.3)}$	$21.0_{(5.9)}$
Extraversion	$13.8_{(5.7)}$	$13.6_{(6.4)}$
Depression	$13.7_{(10.7)}$	$15.5_{(12.6)}$
Life Satisfaction	$19.9_{(8.1)}$	$19.9_{(8.5)}$
Perceived Stress	$14.8_{(6.7)}$	$15.2_{(8.5)}$
Cognitive Empathy	$57.9_{(10.8)}$	$61.0_{(10.8)}$
Affective Empathy	$32.9_{(7.6)}$	$32.9_{(8.2)}$

Table 4. 1 Study 3 demographic and self-report measures

Categorical variables are listed as a percentage of the group total. Means are reported for continuous variables. The numbers in parentheses are standard deviations for continuous variables and the percentage of group total for categorical variables.

Social Positive	Social Negative	Emotional Positive	Emotional Negative	Neutral
Flirt	Lonely	Lucky	Insecure	Barrel
Belong	Inferior	Cheer	Anxious	Board
Included	Selfish	Prize	Frustrated	Bowl
Charming	Disliked	Useful	Irritated	Cabinet
Faithful	Excluded	Pleased	Greed	Chair
Desired	Inadequate	Brave	Afraid	Chin
Devoted	Defeated	Achieve	Stress	Foot
Thoughtful	Insulted	Enjoy	Sad	Hairpin
Accepted	Unwanted	Comfort	Angry	Item
Liked	Shamed	Terrific	Fear	Kettle
Giving	Pathetic	Delight	Distress	Locker
Admired	Deceived	Hope	Panic	Paper
Caring	Hostile	Laugh	Depressed	Pencil
Loyal	Ridiculed	Pleasure	Pain	Seat
Affection	Humiliated	Bliss	Anguish	Square
Kind	Rejected	Fun	Corrupt	Statue
Kiss	Betrayed	Joyful	Brutal	Street
Loved	Abused	Success	Misery	Table
	Assaulted	Happy	Agony	Taxi
			Cruel	

Table 4. 2 List of words used in Stroop Task
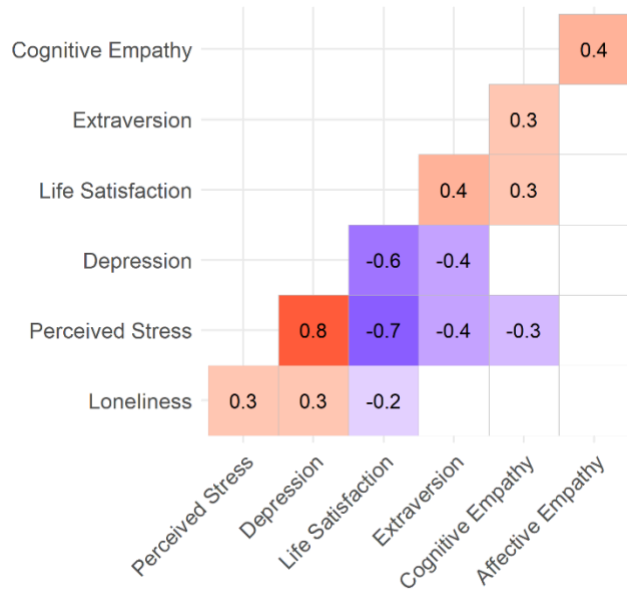
Word list validated by (Faig, 2019)

Figure 4. 1 Study 3 correlation matrix of questionnaires

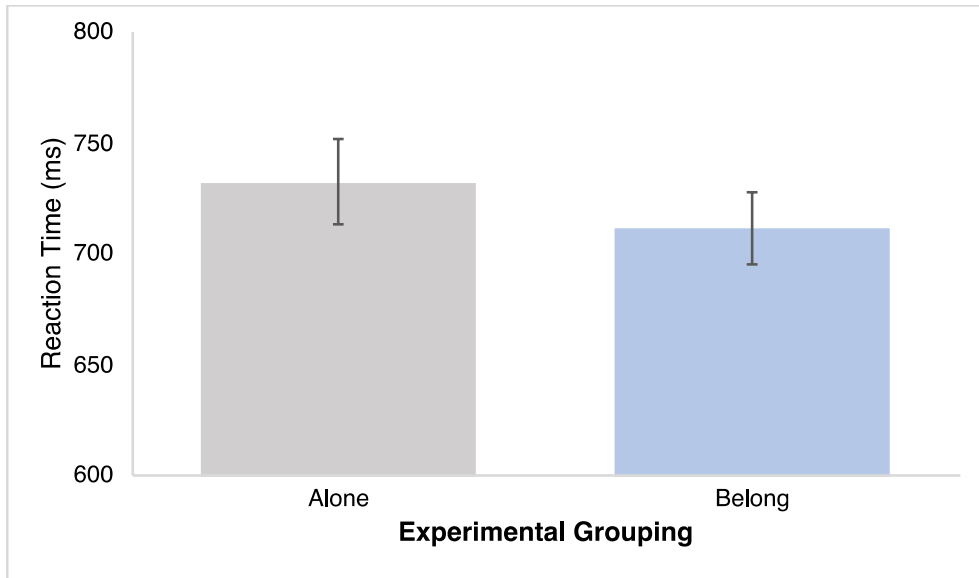Only significant Pearson correlation values are included in this figure.

Figure 4. 2 Stroop Reaction Time: Experimental Grouping

There was no significant difference in Stroop reaction time, across word categories, between the Future Alone and Future Belong groups. Error bars represent the standard error of the mean.
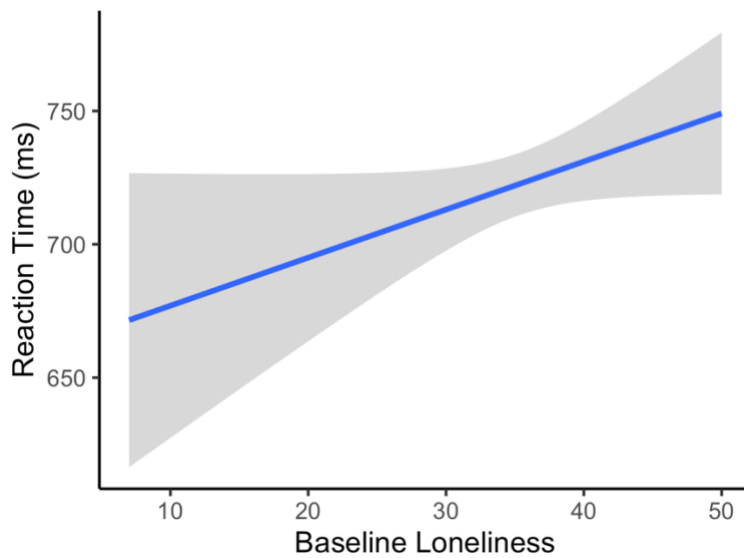

Figure 4. 3 Stroop Reaction Time: Baseline Loneliness
Baseline loneliness did not significantly predict Stroop reaction time across word categories. The shaded grey region represents the standard error of the mean.
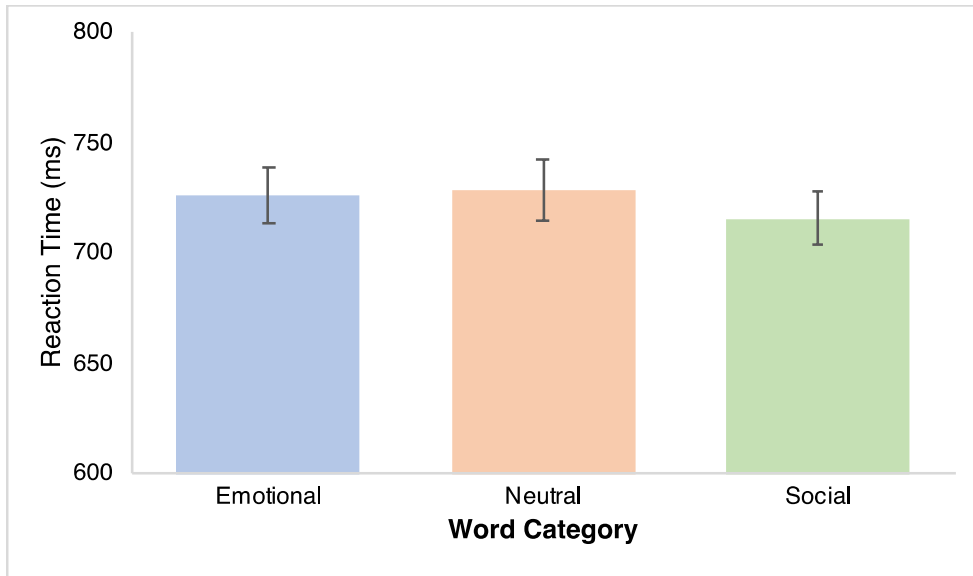
Figure 4. 4 Stroop Reaction Time: Word Category

There was no significant difference in RT between word categories; Social words had a lower, but not statistically significant, RT than neutral or emotional words (β = -10.29, SE = 5.4, CI = [-20.91, 0.34]). Error bars represent the standard error of the mean.
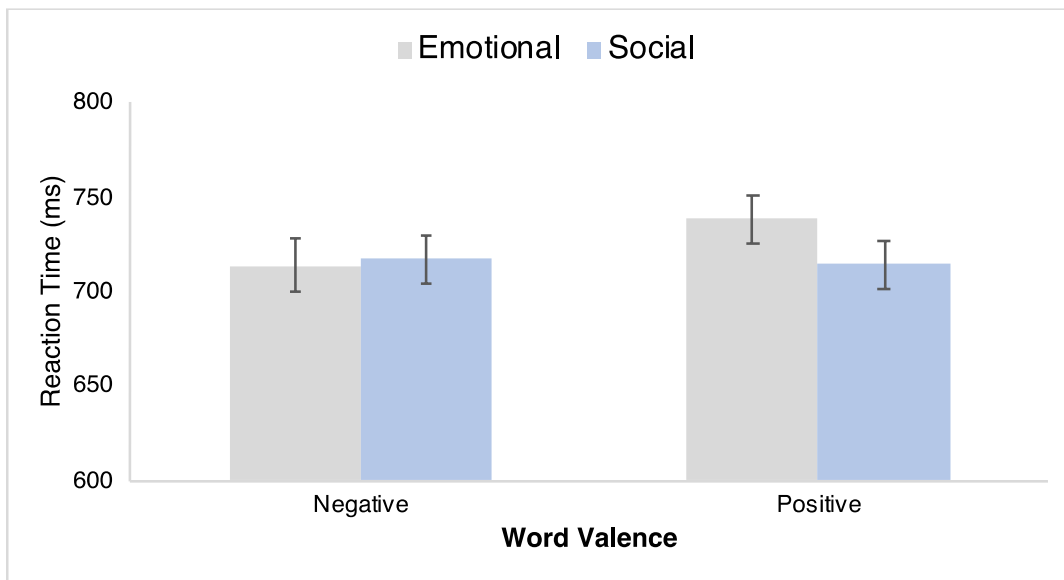

Figure 4. 5 Stroop Reaction Time: Word Category & Valence

There was no significant difference in RT between negative social and negative emotional words. Participants responded more rapidly to social positive words than emotional positive words (β = -24.04, SE = 7.83, CI = [-39.46, -8.62]). Error bars represent the standard error of the mean.
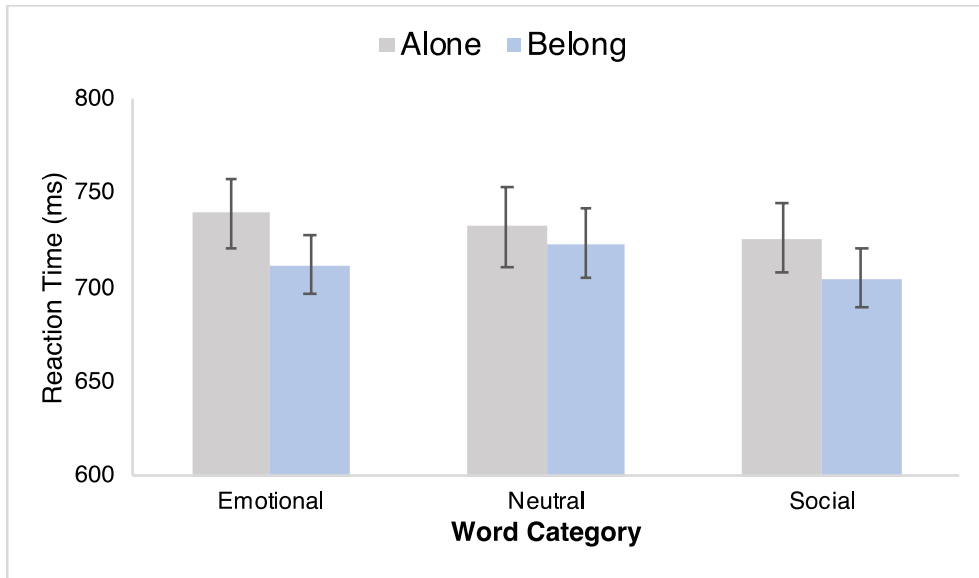
Figure 4. 6 Stroop Reaction Time: Word Category & Experimental Group

There was no significant difference between the Future Alone and Future Belong groups' RT responses to emotional, neutral, and social words. Error bars represent the standard error of the mean.
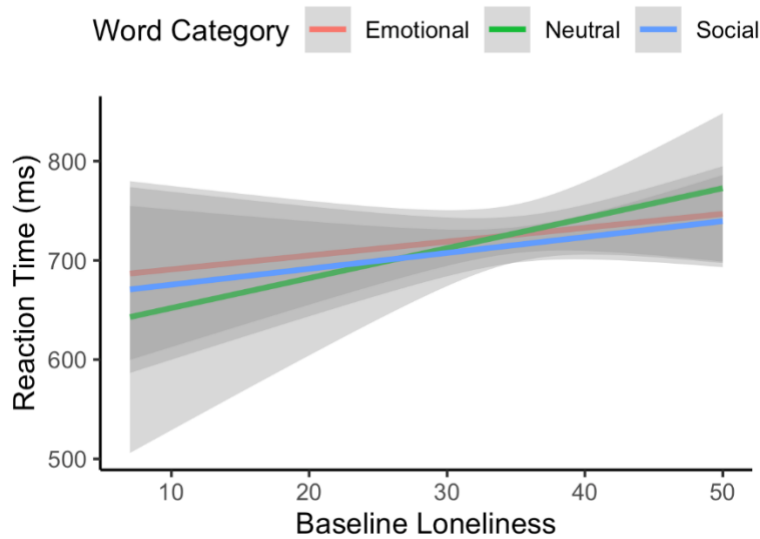
Figure 4. 7 Stroop Reaction Time: Word Category & Baseline Loneliness

Baseline loneliness did not predict RT differences between emotional, neutral, or social words. The grey shaded region represents the standard error of the mean.
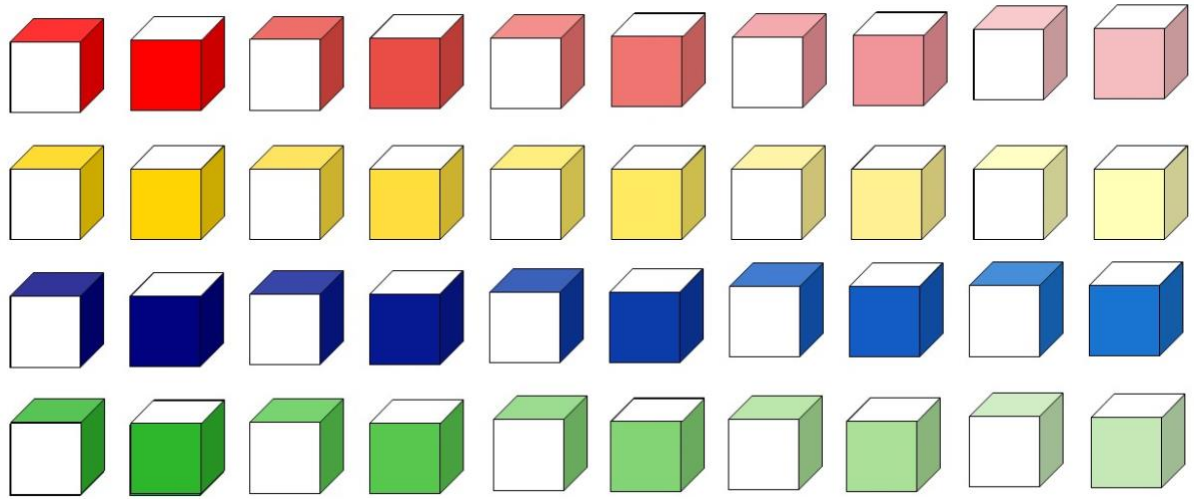
Figure 4. 8 Example non-social stimuli used in the change detection task
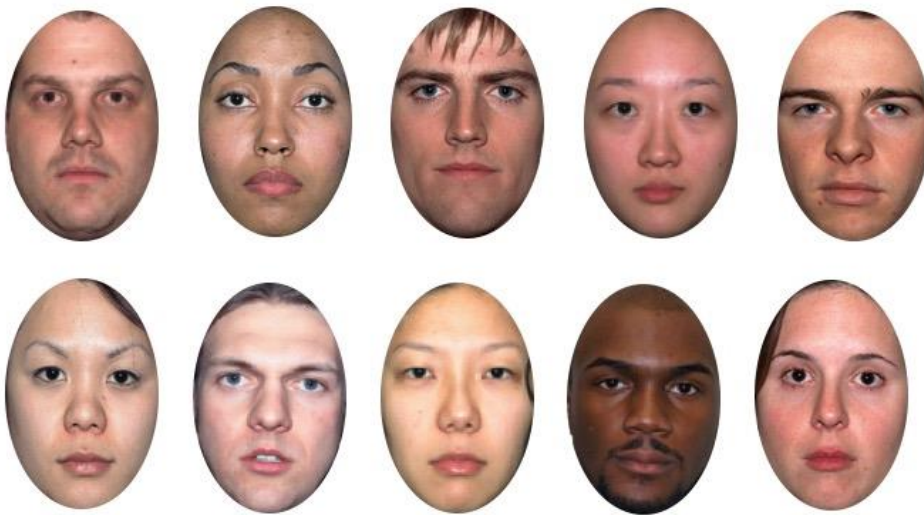
Figure 4. 9 Example social stimuli used in the change detection task

Neutral faces sourced from the Nim-Stim set of facial expressions (Tottenham et al., 2009).
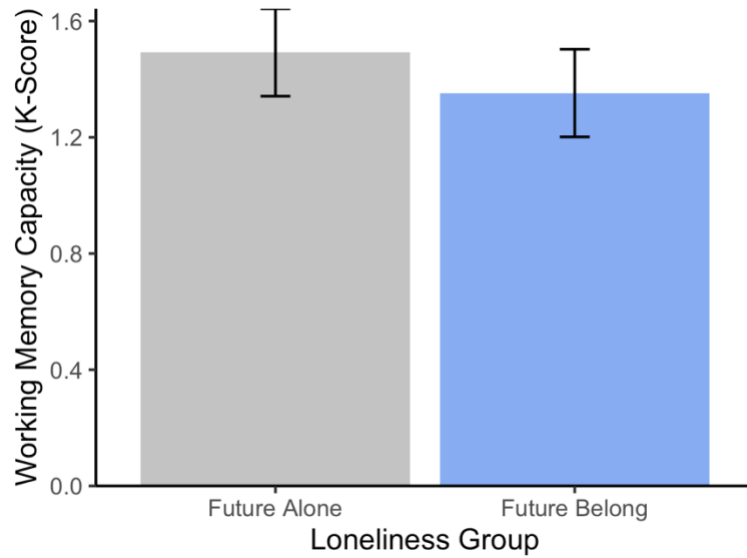
Figure 4. 10 Working Memory Capacity & Experimental Group

There was no significant difference in working memory capacities, across stimulus types, between the Future Alone and Future Belong groups. Error bars represent the standard error of the mean.
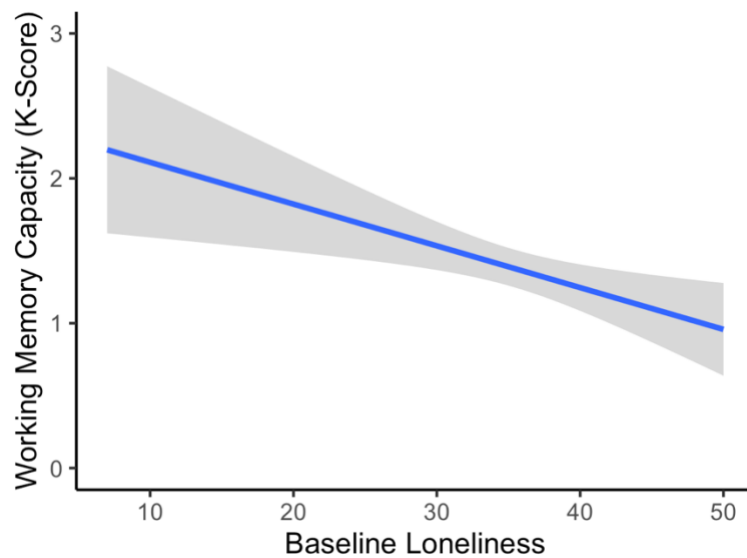
Figure 4. 11 Working Memory Capacity & Baseline Loneliness

Baseline loneliness did not significantly predict working memory capacity across image categories. The grey shaded region represents the standard error of the mean.
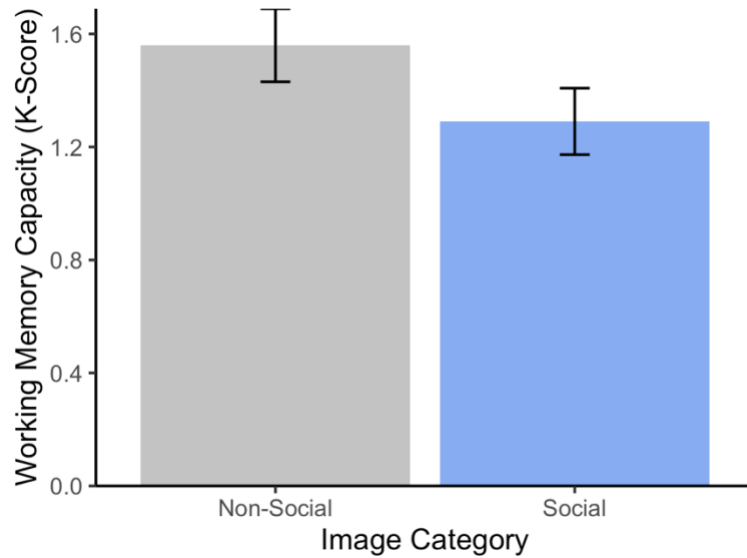
Figure 4. 12 Comparison of Social vs. Non-Social Working Memory Performance

Participants demonstrated higher working memory capacity on non-social trials. $(F_{(1,95)} = 4.58, p < 0.05)$. Error bars represent the standard error of the mean.
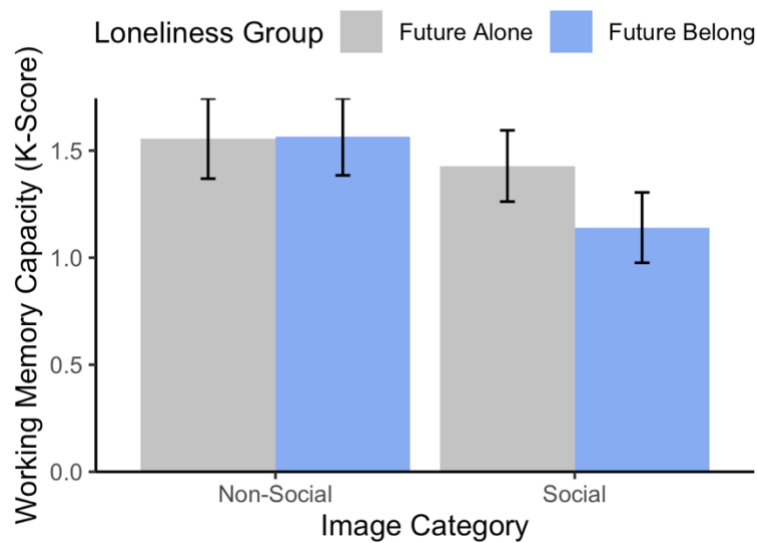
Figure 4. 13 Social vs. Non-Social working memory performance, By Experimental Group

There was no significant interaction between image category and experimental grouping (Future Alone, Future Belong) in predicting working memory capacity. Error bars represent the standard error of the mean.
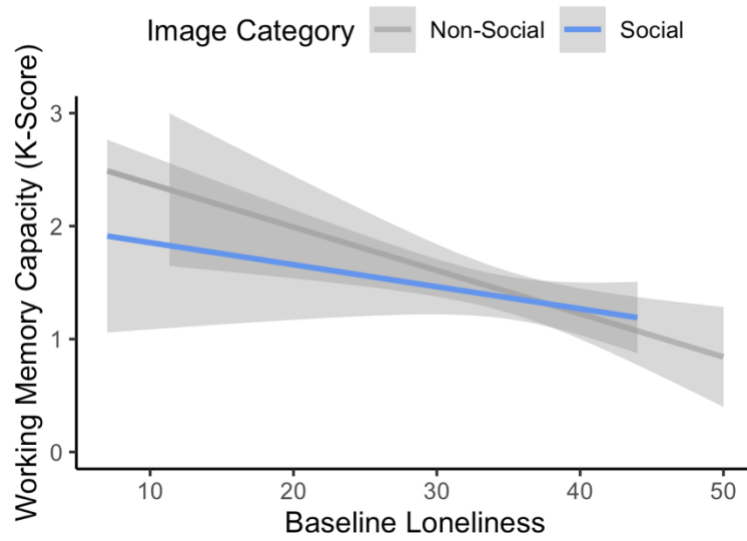
Figure 4. 14 Social vs. Non-Social working memory performance, By Baseline Loneliness

There was no significant interaction between baseline loneliness and image category in predicting working memory capacity. The grey shaded region represents the standard error of the mean

CHAPTER 5: GENERAL CONCLUSIONS

This dissertation represents an examination of social psychophysical regulatory processes associated with a range of competing needs. From the fundamental drive to consume food, motivated by hunger, to much more dynamic socially-oriented motivational processes, such as empathy and loneliness, this dissertation sought to 1) demonstrate how motivation is flexible given environmental demands and 2) how the ANS plays a significant role in the regulation of motivational processes. By examining this wide array of motivational processes, including hunger, pain, empathy, fatigue, and loneliness, I aim to shed light on how motivation shapes psychological, behavioral, and physiological processes. This dissertation also seeks to motivate the multi-level study of the mechanisms that give rise to motivational shifts that allow individuals to survive and prosper. The three studies outlined above included self-report, behavioral, and physiological measures to maximize our understanding of the constructs measured.

Study 1 investigated the relationship between fatigue and the autonomic nervous system. Counter to our predictions, PNS activity rose with mental fatigue, and SNS activity dropped over 90 minutes. While past work has shown that mental fatigue may be associated with drops in PNS activity (Mizuno et al., 2014), other literature suggests that sustained attention is related to increases in PNS activity over time (Pattyn et al., 2008). Given the strong relationship between time, mental fatigue ratings, and PNS activity, I believe fatigue directly increased PNS activity throughout the mental fatigue task. Continuing to elucidate the physiological manifestation of fatigue will aid in diagnosing and treating fatigue-associated disorders such as chronic fatigue syndrome and depression. Indeed, if mental and physical fatigue represent a single phenomenon, it is likely that physical fatigue may impact mental fatigue in the same way that mental fatigue

81

impacts physical fatigue. A limitation of our study was that I did not have a control group of subjects who did not experience mental fatigue induction before physical fatigue induction. While there is ample evidence to suggest that mental fatigue impacts physical fatigue and performance (Cutsem et al., 2017), less is known about the potential impact of physical fatigue on mental fatigue and cognitive performance. Examining autonomic activity when physical activity precedes a mentally fatiguing task will complement our current analyses and provide additional insight into the psychophysiological regulatory mechanisms associated with fatigue.

Study 2, described in Chapter 3, investigated hunger's role in motivational competition with another visceral need and socially-oriented motivation. I first examined state affect and found no influence of our hunger manipulation on positive or negative affect. Past work has demonstrated hunger's impact on highly valanced negative emotions such as aggression (Fattorini et al., 2018) and anger (Awathale et al., 2020). Our study indicates that there may be no direct relationship between hunger and negative affect in general. Next, I hypothesized that hungry participants would show diminished empathy. I found no significant relationships between hunger and self-reported cognitive or affective empathy. Additionally, there were no significant differences between individuals in the sensitivity to the pain of others as a function of hunger. Although past work has suggested that empathy is flexible given interpersonal and contextual factors (Decety, 2015b), short-term hunger may be too mild of a stressor to influence empathy directly. I hypothesized that hungry participants would show a dampened pain response resulting from the motivational prioritization of hunger. I saw no significant relationship between hunger and behavioral responses to pain. These data suggest that acute hunger may not influence shifts in acute pain perception. One potential explanation for this is that acute pain must be prioritized over hunger in most contexts. While hunger-induced chronic pain dampening has

been previously reported (Bosley et al., 2004), additional work in human populations is needed to understand the relationship between hunger and acute pain. I found a significant effect between hunger and baseline PNS cardiac control. Subjects in the hunger induction group had higher resting hf-HRV values than subjects in the control group, potentially indicating heightened emotional and physiological flexibility (Kok & Fredrickson, 2010

Our study's findings provide little evidence for direct motivational shifts within the domains of acute hunger, positive or negative empathy, pain, and empathy after acute hunger induction. Hunger is an integral component of allostatic regulation, yet many unanswered questions about how this life-sustaining motivation interacts with co-occurring motivational processes. Examining hunger using a more comprehensive range of fasting durations will allow us to understand better how hunger's magnitude plays a role in dynamic motivational systems.

Finally, Study 3 investigated perceived social isolation and motivated cognition. I hypothesized that loneliness would be associated with attentional biases towards negative and social stimuli. I administered a social and emotional Stroop task, attempting to replicate past work examining the effect of loneliness on attentional biases to social stimuli (S. Cacioppo et al., 2015). I did not find any main effects of baseline loneliness on Stroop performance across word categories or valence. I also did not find any main effects of experimental grouping (Future Alone/Future Belong) on Stroop performance across word categories or valence. I believe that my results did not replicate past findings because of the experimental context (online vs. in-lab).

Past evidence of loneliness induced attentional biases to social stimuli has primarily been found at the neural level. I examined attentional biases at the behavioral level throughout Study 3, with the hypothesis that loneliness would increase working memory capacity to social stimuli. I did not see any effect of loneliness on either social or non-social working memory capacity.

While this result was counter to our predictions, this result suggests that loneliness in healthy adults may not impact working memory capacity. Perhaps working memory is only affected when loneliness is chronic or coincides with depression (as is documented in prior work). This study demonstrates that loneliness may not affect attention or working memory capacity in healthy adults. Limitations of the study include online administration and relatively low loneliness values in the sample.

Taken together, these three studies underscore the dynamic nature of psychophysiological systems and motivate future investigation into how social and non-social motivational processes interact. Future work investigating motivation and the autonomic nervous system should continue to investigate competing motivational processes in varied contexts. Continued multi-level analysis of human motivational competition will inform our understanding of how individuals maintain stability in ever-changing environments.

REFERENCES

Adolph, E. F. (1961). Early concepts of physiological regulations. *Physiological Reviews*, *41*(4), 737–770.

Alhadeff, A. L., Su, Z., Hernandez, E., Klima, M. L., Phillips, S. Z., Holland, R. A., Guo, C., Hantman, A. W., De Jonghe, B. C., & Betley, J. N. (2018). A Neural Circuit for the Suppression of Pain by a Competing Need State. *Cell*, *173*(1), 140-152.e15. https://doi.org/10.1016/J.CELL.2018.02.057

Arai, Y., Saul, J. P., Albrecht, P., Hartley, L. H., Lilly, L. S., Cohen, R. J., & Colucci, W. S. (1989). Modulation of cardiac autonomic activity during and immediately after exercise. *American Journal of Physiology-Heart and Circulatory Physiology*, *256*(1), H132–H141. https://doi.org/10.1152/ajpheart.1989.256.1.H132

Aubert, A., Goodall, G., Dantzer, R., & Gheusi, G. (1997). Differential Effects of Lipopolysaccharide on Pup Retrieving and Nest Building in Lactating Mice. *Brain, Behavior, and Immunity*, *11*(2), 107–118. https://doi.org/10.1006/brbi.1997.0485

Bakdash, J. Z., & Marusich, L. R. (2017). Repeated measures correlation. *Frontiers in Psychology*, *8*, 456.

Ballesteros, S., Reales, J., & Manga, D. (2000). Effects of Type of Design (Blocked vs. Randomized) on Stroop and Emotional Stroop Tasks. *Psicothema*, *12*.

Bates, D., Sarkar, D., Bates, M. D., & Matrix, L. (2007). The lme4 package. *R Package Version*, *2*(1), 74.

Batterink, L., Yokum, S., & Stice, E. (2010). Body mass correlates inversely with inhibitory control in response to food among adolescent girls: An fMRI study. *NeuroImage*, *52*(4), 1696–1703.

Baumeister, R. F., DeWall, C. N., Ciarocco, N. J., & Twenge, J. M. (2005). Social exclusion impairs self-regulation. *Journal of Personality and Social Psychology*, *88*(4), 589.

Baumeister, R., Twenge, J., & Nuss, C. (2002). Effects of social exclusion on cognitive processes: Anticipated aloneness reduces intelligent thought. *Journal of Personality and Social Psychology*, *83*, 817–827.

Benarroch, E. E. (2012). Central autonomic control. In *Primer on the autonomic nervous system* (pp. 9–12). Elsevier.

Bernard, C. (1879). *Leçons sur les phénomènes de la vie commune aux animaux et aux végétaux* (Vol. 2). Baillière.

Billman, G. E. (2020). Homeostasis: The Underappreciated and Far Too Often Ignored Central Organizing Principle of Physiology. *Frontiers in Physiology*, *11*.

Blessing, B., & Gibbins, I. (2008). Autonomic Nervous System. *Scholarpedia*, *3*(7), 2787. https://doi.org/10.4249/scholarpedia.2787

Boksem, M. A. S., & Tops, M. (2008). Mental fatigue: Costs and benefits. *Brain Research Reviews*, *59*(1), 125–139. https://doi.org/10.1016/j.brainresrev.2008.07.001

Borg, G. (1982). Ratings of Perceived Exertion and Heart Rates During Short-Term Cycle Exercise and Their Use in a New Cycling Strength Test*. *International Journal of Sports Medicine*, *03*(03), 153–158. https://doi.org/10.1055/s-2008-1026080

Bosley, B. N., Weiner, D. K., Rudy, T. E., & Granieri, E. (2004). Is Chronic Nonmalignant Pain Associated with Decreased Appetite in Older Adults? Preliminary Evidence. *Journal of the American Geriatrics Society*, *52*(2), 247–251. https://doi.org/10.1111/j.1532-5415.2004.52063.x

Brown, D. M., Graham, J. D., Innes, K. I., Harris, S., Flemington, A., & Bray, S. R. (2020). Effects of prior cognitive exertion on physical performance: A systematic review and meta-analysis. *Sports Medicine*, *50*(3), 497–529.

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences*, *4*(6), 215–222. https://doi.org/10.1016/S1364-6613(00)01483-2

Butler, E. A., Wilhelm, F. H., & Gross, J. J. (2006). Respiratory sinus arrhythmia, emotion, and emotion regulation during social interaction. *Psychophysiology*, *43*(6), 612–622.

Cacioppo, J. T., & Cacioppo, S. (2014). Older adults reporting social isolation or loneliness show poorer cognitive function 4 years later. *Evidence-Based Nursing*, *17*(2), 59–60. https://doi.org/10.1136/eb-2013-101379

Cacioppo, J. T., & Cacioppo, S. (2018). Loneliness in the modern age: An evolutionary theory of loneliness (ETL). In *Advances in experimental social psychology* (Vol. 58, pp. 127–197). Elsevier.

Cacioppo, J. T., Cacioppo, S., & Boomsma, D. I. (2014). Evolutionary mechanisms for loneliness. *Cognition and Emotion*, *28*(1), 3–21. https://doi.org/10.1080/02699931.2013.837379

Cacioppo, J. T., & Hawkley, L. C. (2009a). Loneliness. In *Handbook of individual differences in social behavior* (pp. 227–240). The Guilford Press.

Cacioppo, J. T., & Hawkley, L. C. (2009b). Perceived social isolation and cognition. *Trends in Cognitive Sciences*, *13*(10), 447–454. https://doi.org/10.1016/j.tics.2009.06.005

Cacioppo, J. T., Hawkley, L. C., Crawford, L. E., Ernst, J. M., Burleson, M. H., Kowalewski, R. B., Malarkey, W. B., Van Cauter, E., & Berntson, G. G. (2002). Loneliness and Health: Potential Mechanisms. *Psychosomatic Medicine*, *64*(3), 407–417.

Cacioppo, J. T., Hughes, M. E., Waite, L. J., Hawkley, L. C., & Thisted, R. A. (2006). Loneliness as a specific risk factor for depressive symptoms: Cross-sectional and longitudinal analyses. *Psychology and Aging*, *21*(1), 140.

Cacioppo, J. T., Uchino, B. N., & Berntson, G. G. (1994). Individual differences in the autonomic origins of heart rate reactivity: The psychometrics of respiratory sinus arrhythmia and preejection period. *Psychophysiology*, *31*(4), 412–419. https://doi.org/10.1111/j.1469-8986.1994.tb02449.x

Cacioppo, S., Balogh, S., & Cacioppo, J. T. (2015). Implicit attention to negative social, in contrast to nonsocial, words in the Stroop task differs between individuals high and low in loneliness: Evidence from event-related brain microstates. *Cortex*, *70*, 213–233. https://doi.org/10.1016/j.cortex.2015.05.032

Campfield, L. A. , S. F. J. , R. M. , & H. J. (1996). Human eating: Evidence for a physiological basis using a modified paradigm. *Neuroscience and Biobehavioral Reviews* , *20*(1), 133–137.

Cannon, W. B. (1939). *The wisdom of the body*.

Cimprich, B., Visovatti, M., & Ronis, D. L. (2011). The Attentional Function Index-a self-report cognitive measure. *Psycho-Oncology*, *20*(2), 194–202. https://doi.org/10.1002/pon.1729

Cofer, C. N., & Appley, M. H. (1964). *Motivation: Theory and research* (p. 958). John Wiley.

Cohen, S. (n.d.). *PERCEIVED STRESS SCALE*. 5.

Cooper, K., Hards, E., Moltrecht, B., Reynolds, S., Shum, A., McElroy, E., & Loades, M. (2021). Loneliness, social relationships, and mental health in adolescents during the COVID-19 pandemic. *Journal of Affective Disorders*, *289*, 98–104. https://doi.org/10.1016/j.jad.2021.04.016

Cortelli, P., Giannini, G., Favoni, V., Cevoli, S., & Pierangeli, G. (2013). Nociception and autonomic nervous system. *Neurological Sciences*, *34*(SUPPL. 1). https://doi.org/10.1007/s10072-013-1391-z

Cosmides, L., & Tooby, J. (2000). Evolutionary Psychology and the Emotions. *Handbook of Emotions*, *2*, 91–115. https://doi.org/10.1007/978-94-007-1951-4

Craig, C. L., Marshall, A. L., M, M. S. S., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J. F., Oja, P., Craig, C. L., Marshall, A. L., Strö, M. S., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U., … Oja, P. (2003). International physical activity questionnaire: 12-country reliability and validity,". *Medicine and Science in Sports and Exercise,* 1381–1395.

Critchley, Elliott, R., Mathias, CJ., & Dolan, RJ. (2013). Neural Activity Relating to Generation and Representation of Galvanic Skin Conductance Responses: A Functional Magnetic Resonance Imaging Study. *Journal of Neuroscience*, *20*(8), 3033–3040.

Critchley, H. D., & Garfinkel, S. N. (2017). Interoception and emotion. In *Current Opinion in Psychology* (Vol. 17, pp. 7–14). Elsevier B.V. https://doi.org/10.1016/j.copsyc.2017.04.020

Cutsem, J. V., Marcora, S., & Pauw, K. D. (2017). The effects of mental fatigue on physical performance: A systematic review. *Sports Medicine*, *47*(8), 1569–1588. https://doi.org/10.1007/s40279-016-0672-0

Cutsem, J. V., Meeusen, R., Roelands, B., & Marcora, S. (2018). *The link between mental fatigue and physical performance*. https://kar.kent.ac.uk/73779/1/282PhD - Van Cutsem Jeroen FINAL.pdf

Decety, J. (2011). The neuroevolution of empathy. *Ann. N.Y. Acad. Sci*, *1231*(1), 35–45. https://doi.org/10.1111/j.1749-6632.2011.06027.x

Decety, J. (2015). The neural pathways, development and functions of empathy. *Current Opinion in Behavioral Sciences*, *3*, 1–6. https://doi.org/10.1016/j.cobeha.2014.12.001

Decety, J., Echols, S., & Correll, J. (2010). The Blame Game: The Effect of Responsibility and Social Stigma on Empathy for Pain. *Journal of Cognitive Neuroscience*, *22*(5), 985–997. https://doi.org/10.1162/jocn.2009.21266

Decety, J., Norman, G. J., Berntson, G. G., & Cacioppo, J. T. (2012). A neurobehavioral evolutionary perspective on the mechanisms underlying empathy. In *Progress in Neurobiology* (Vol. 98, Issue 1, pp. 38–48). Pergamon. https://doi.org/10.1016/j.pneurobio.2012.05.001

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, *64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Diener, E., Emmons, R. A., Larsen, R. J., & Griffin, S. (1985). The Satisfaction With Life Scale. *Journal of Personality Assessment*, *49*(1), 71–75. https://doi.org/10.1207/s15327752jpa4901_13

Dixon, L. M., Brocklehurst, S., Sandilands, V., Bateson, M., Tolkamp, B. J., & D'Eath, R. B. (2014). Measuring motivation for appetitive behaviour: Food-restricted broiler breeder chickens cross a water barrier to forage in an area of wood shavings without food. *PLoS ONE*, *9*(7). https://doi.org/10.1371/journal.pone.0102322

Dobryakova, E., DeLuca, J., Genova, H. M., & Wylie, G. R. (2013). Neural correlates of cognitive fatigue: Cortico-striatal circuitry and effort–reward imbalance. *Journal of the International Neuropsychological Society*, *19*(8), 849–853.

Donovan, N. J., Wu, Q., Rentz, D. M., Sperling, R. A., Marshall, G. A., & Glymour, M. M. (2017). Loneliness, depression and cognitive function in older US adults. *International Journal of Geriatric Psychiatry*, *32*(5), 564–573.

Drazen, D., & Woods, S. (2003). Peripheral signals in the control of satiety and hunger. *Current Opinion in Clinical Nutrition*, *6*(6), 621–6329.

Dunning, D. (2011). *Social Motivation*. Psychology Press.

Dupré, J., & O'Malley, M. A. (2013). Varieties of living things: Life at the intersection of lineage and metabolism. In *Vitalism and the Scientific Image in Post-Enlightenment Life Science, 1800-2010* (pp. 311–343). Springer.

Eccles, A. M., & Qualter, P. (2021). Review: Alleviating loneliness in young people – a meta-analysis of interventions. *Child and Adolescent Mental Health*, *26*(1), 17–33. https://doi.org/10.1111/camh.12389

Faig, K. (2019). *The Psychophysiology of Social Behavior: A Focus on the Behavioral Immune System*. The University of Chicago.

Fisher, J. P., Young, C. N., & Fadel, P. J. (2015). Autonomic adjustments to exercise in humans. *Comprehensive Physiology*, *5*(2), 475–512. https://doi.org/10.1002/cphy.c140022

Friedman, M. I., Ulrich, P., & Mattes, R. D. (1999). A figurative measure of subjective hunger sensations. *Appetite*, *32*(3), 395–404. https://doi.org/10.1006/appe.1999.0230

Gailliot, M. T. (2013). Hunger and Reduced Self-Control in the Laboratory and across the World: Reducing Hunger as a Self-Control Panacea. *Psychology*, *4*(1), 59–66. https://doi.org/10.4236/psych.2013.41008

Gao, M., Shao, R., Huang, C.-M., Liu, H.-L., Chen, Y.-L., Lee, S.-H., Lin, C., & Lee, T. M. C. (2020). The relationship between loneliness and working-memory-related frontoparietal network connectivity in people with major depressive disorder. *Behavioural Brain Research*, *393*, 112776. https://doi.org/10.1016/j.bbr.2020.112776

Garatachea, N., Cavalcanti, E., García-López, D., González-Gallego, J., & de Paz, J. A. (2007). Estimation of Energy Expenditure in Healthy Adults From the YMCA Submaximal Cycle Ergometer Test. *Evaluation & the Health Professions*, *30*(2), 138–149. https://doi.org/10.1177/0163278707300628

Gawron, V. J., French, J., & Funke, D. (2001). An overview of fatigue. In *Stress, workload, and fatigue* (pp. 581–595). Lawrence Erlbaum Associates Publishers.

Gianaros, P. J., Onyewuenyi, I. C., Sheu, L. K., Christie, I. C., & Critchley, H. D. (2012). Brain systems for baroreflex suppression during stress in humans. *Human Brain Mapping*, *33*(7), 1700–1716.

Gilgen-Ammann, R., Schweizer, T., & Wyss, T. (2019). RR interval signal quality of a heart rate monitor and an ECG Holter at rest and during exercise. *European Journal of Applied Physiology*, *119*(7), 1525–1532. https://doi.org/10.1007/s00421-019-04142-5

Golding, L. A., Myers, C. R., SINNING, K. E., Golding, L., Myers, C., & Sinning, S. (1989). *Y's way to Physical Fitness: The Complete Guide to Fitness Testing and Instruction*.

Goldstein, D. S., & McEwen, B. (2002). Allostasis, Homeostats, and the Nature of Stress. *Stress*, *5*(1), 55–58. https://doi.org/10.1080/102538902900012345

Groenewegen, H. J., & Uylings, H. B. M. (2000). The prefrontal cortex and the integration of sensory, limbic and autonomic information. In *Progress in Brain Research* (Vol. 126, pp. 3–28). Elsevier. https://doi.org/10.1016/S0079-6123(00)26003-2

Gronwald, T., Ludyga, S., Hoos, O., & Hottenrott, K. (2018). Non-linear dynamics of cardiac autonomic activity during cycling exercise with varied cadence. *Human Movement Science*, *60*, 225–233. https://doi.org/10.1016/j.humov.2018.06.013

Gross, C. G. (1998). Claude Bernard and the Constancy of the Internal Environment. *The Neuroscientist*, *4*(5), 380–385. https://doi.org/10.1177/107385849800400520

Havel, P. J., & Taborsky, G. J. (1989). The Contribution of the Autonomic Nervous System to Changes of Glucagon and Insulin Secretion during Hypoglycemic Stress*. *Endocrine Reviews*, *10*(3), 332–350.

Hawkley, L. C., & Cacioppo, J. T. (2010). Loneliness matters: A theoretical and empirical review of consequences and mechanisms. *Annals of Behavioral Medicine*, *40*(2), 218–227.

Hawkley, L. C., Masi, C. M., Berry, J. D., & Cacioppo, J. T. (2006). Loneliness is a unique predictor of age-related differences in systolic blood pressure. *Psychology and Aging*, *21*(1), 152.

Heart rate variability and autonomic activity at rest and during exercise in various physiological conditions. (n.d.). https://doi.org/10.1007/s00421-003-0953-9

Hockey, B., & Hockey, R. (2013). *The psychology of fatigue: Work, effort and control*.

Holle, C., Neely, J. H., & Heimberg, R. G. (1997). The effects of blocked versus random presentation and semantic relatedness of stimulus words on response to a modified Stroop task among social phobics. *Cognitive Therapy and Research*, *21*(6), 681–697.

Hoshikawa, Y., & Yamamoto, Y. (1997). Effects of stroop color-word conflict test on the autonomie nervous system responses. *American Journal of Physiology*, *272*(3 PART 2). https://doi.org/10.1152/ajpheart.1997.272.3.h1113

Hughes, M. E., Waite, L. J., Hawkley, L. C., & Cacioppo, J. T. (2004). A Short Scale for Measuring Loneliness in Large Surveys: Results From Two Population-Based Studies. *Research on Aging*, *26*(6), 655–672. https://doi.org/10.1177/0164027504268574

Huppert, E., Shaw, A., & Decety, J. (2020). The effect of hunger on children's sharing behavior and fairness preferences. *Journal of Experimental Child Psychology*. https://doi.org/10.1016/j.jecp.2019.104786

Inagaki, T. K., Muscatell, K. A., Moieni, M., Dutcher, J. M., Jevtic, I., Irwin, M. R., & Eisenberger, N. I. (2016). Yearning for connection? Loneliness is associated with increased ventral striatum activity to close others. *Social Cognitive and Affective Neuroscience*, *11*(7), 1096–1101. https://doi.org/10.1093/scan/nsv076

Janowitz, H. D., & Grossman, M. I. (1949). *Gusto-Olfactory Thresholds in Relation to Appetite and Hunger Sensations*. *Journal of Applied Physiology*, *2*(4), 217–222. https://doi.org/10.1152/jappl.1949.2.4.217

Kim, J., Gabriel, U., & Gygax, P. (2019). Testing the effectiveness of the Internet-based instrument PsyToolkit: A comparison between web-based (PsyToolkit) and lab-based (E-Prime 3.0) measurements of response choice and response time in a complex psycholinguistic task. *PLOS ONE*, *14*(9), e0221802. https://doi.org/10.1371/journal.pone.0221802

Kok, B. E., & Fredrickson, B. L. (2010). Upward spirals of the heart: Autonomic flexibility, as indexed by vagal tone, reciprocally and prospectively predicts positive emotions and social connectedness. *Biological Psychology*, *85*(3), 432–436. https://doi.org/10.1016/j.biopsycho.2010.09.005

Koto, A., Mersch, D., Hollis, B., & Keller, L. (2015). Social isolation causes mortality by disrupting energy homeostasis in ants. *Behavioral Ecology and Sociobiology*, *69*(4), 583–591. https://doi.org/10.1007/s00265-014-1869-6

Kreibig, S. D. (2010). Autonomic nervous system activity in emotion: A review. *Biological Psychology*, *84*(3), 394–421. https://doi.org/10.1016/J.BIOPSYCHO.2010.03.010

Lang, P. J. (2010). Emotion and Motivation: Toward Consensus Definitions and a Common Research Purpose. *Emotion Review*, *2*(3), 229–233. https://doi.org/10.1177/1754073910361984

Large, M.-E., Cavina-Pratesi, C., Vilis, T., & Culham, J. C. (2008). The neural correlates of change detection in the face perception network. *Neuropsychologia*, *46*(8), 2169–2176. https://doi.org/10.1016/j.neuropsychologia.2008.02.027

Le Bras, A. (2021). Effect of chronic social isolation on flies. *Lab Animal*, *50*(10), 281–281. https://doi.org/10.1038/s41684-021-00866-0

Leone, M., Proietti Cecchini, A., Mea, E., Tullo, V., Curone, M., & Bussone, G. (2006). Neuroimaging and pain: A window on the autonomic nervous system. *Neurological Sciences*, *27*(SUPPL. 2). https://doi.org/10.1007/s10072-006-0588-9

Leong, L. E. M., Cano, A., Wurm, L. H., Lumley, M. A., & Corley, A. M. (2015). A Perspective-Taking Manipulation Leads to Greater Empathy and Less Pain during the

Cold Pressor Task. *Journal of Pain*, *16*(11), 1176–1185. https://doi.org/10.1016/j.jpain.2015.08.006

Lovallo, W. (1975). *The Cold Pressor Test and Autonomic Function: A Review and Integration* (Vol. 12, Issue 3).

Macmahon, C., Hagemann, N., & Strauss, B. (n.d.). *Cognitive Fatigue Effects on Physical Performance During Running*. https://doi.org/10.1123/jsep.2013-0249

Mager, D. E., Wan, R., Brown, M., Cheng, A., Wareski, P., Abernethy, D. R., & Mattson, M. P. (2006). Caloric restriction and intermittent fasting alter spectral measures of heart rate and blood pressure variability in rats Effects of buildings on human health and performance View project Mitochondria response in Neurodegenerative diseases View project Caloric restriction and intermittent fasting alter spectral measures of heart rate and blood pressure variability in rats. *Article in The FASEB Journal*. https://doi.org/10.1096/fj.05-5263com

Mailund, T. (2019). Manipulating data frames: Dplyr. In *R Data Science Quick Reference* (pp. 109–160). Springer.

Marcora, S. M., & Staiano, W. (2009). Mental fatigue impairs physical performance in humans Impact of 4-week Brain Endurance Training (BET) on Cognitive and Physical Performance in Professional Football Players View project Psychobiology of Endurance Performance View project. *Article in Journal of Applied Physiology*. https://doi.org/10.1152/japplphysiol.91324.2008

Martín-María, N., Caballero, F. F., Miret, M., Tyrovolas, S., Haro, J. M., Ayuso-Mateos, J. L., & Chatterji, S. (2020). Differential impact of transient and chronic loneliness on health status. A longitudinal study. *Psychology & Health*, *35*(2), 177–195. https://doi.org/10.1080/08870446.2019.1632312

Matthews-Ewald, M. R., & Zullig, K. J. (2013). Evaluating the performance of a short loneliness scale among college students. *Journal of College Student Development*, *54*(1), 105–109.

McCorry, L. K. (2007). Physiology of the Autonomic Nervous System. *American Journal of Pharmaceutical Education*, *71*(4). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1959222/

McEwen, B. S., & Wingfield, J. C. (2003). The concept of allostasis in biology and biomedicine. *Hormones and Behavior*, *43*(1), 2–15. https://doi.org/10.1016/S0018-506X(02)00024-7

McFarland, D. (1964). Interaction of hunger and thirst in the Barbary dove. *Journal of Comparative and Physiological Psychology*, 174–169.

McMorris, T., Barwood, M., & Corbett, J. (2018). Central fatigue theory and endurance exercise: Toward an interoceptive model. *Neuroscience and Biobehavioral Reviews*, *93*, 93–107. https://doi.org/10.1016/j.neubiorev.2018.03.024

Meeusen, R., & Roelands, B. (2018). Fatigue: Is it all neurochemistry? *European Journal of Sport Science*, *18*(1), 37–46.

Mehta, R., factors, R. P.-H., & 2014, undefined. (2013). Effects of mental fatigue on the development of physical fatigue: A neuroergonomic approach. *Journals.Sagepub.Com*, *56*(4), 645–656. https://doi.org/10.1177/0018720813507279

Mendoza, T. R., Wang, X. S., Cleeland, C. S., Morrissey, M., Johnson, B. A., Wendt, J. K., & Huber, S. L. (1999). The rapid assessment of fatigue severity in cancer patients. *Cancer*, *85*(5), 1186–1196. https://doi.org/10.1002/(SICI)1097-0142(19990301)85:5<1186::AID-CNCR24>3.0.CO;2-N

Michalsen, A. (2010). Prolonged fasting as a method of mood enhancement in chronic pain syndromes: A review of clinical evidence and mechanisms. In *Current Pain and Headache Reports* (Vol. 14, Issue 2, pp. 80–87). Springer. https://doi.org/10.1007/s11916-010-0104-z

Mindware Technology, Gahanna, OH. (n.d.). *Mindware Technology*.

Mitchell, L. A., MacDonald, R. A. R., & Brodie, E. E. (2004). Temperature and the cold pressor test. *The Journal of Pain*, *5*(4), 233–237. https://doi.org/10.1016/J.JPAIN.2004.03.004

Mizuno, K., Tanaka, M., Yamaguti, K., Kajimoto, O., Kuratsune, H., & Watanabe, Y. (2011). Mental fatigue caused by prolonged cognitive load associated with sympathetic hyperactivity. *Behavioral and Brain Functions*, *7*(1), 17–17. https://doi.org/10.1186/1744-9081-7-17

Montoliu, T., Hidalgo, V., & Salvador, A. (2019). The relationship between loneliness and cognition in healthy older men and women: The role of cortisol. *Psychoneuroendocrinology*, *107*, 270–279.

Norman, G. J., Berntson, G. G., & Cacioppo, J. T. (2014). Emotion, Somatovisceral Afference, and Autonomic Regulation. *Emotion Review*, *6*(2), 113–123. https://doi.org/10.1177/1754073913512006

Nowland, R., Robinson, S. J., Bradley, B. F., Summers, V., & Qualter, P. (2018). Loneliness, HPA stress reactivity and social threat sensitivity: Analyzing naturalistic social challenges. *Scandinavian Journal of Psychology*, *59*(5), 540–546.

O'luanaigh, C., O'connell, H., Chin, A.-V., Hamilton, F., Coen, R., Walsh, C., Walsh, J. B., Caokley, D., Cunningham, C., & Lawlor, B. A. (2012). Loneliness and cognition in older people: The Dublin Healthy Ageing study. *Aging & Mental Health*, *16*(3), 347–352.

Piejka, A., Wiśniewska, M., Thayer, J. F., & Okruszek, Ł. (2021). Brief induction of loneliness decreases vagal regulation during social information processing. *International Journal of Psychophysiology*, *164*, 112–120. https://doi.org/10.1016/j.ijpsycho.2021.03.002

Powley, T. L. (2009). Hunger. In *Handbook of Neuroscience for the Behavioral Sciences*. John Wiley & Sons, Inc. https://doi.org/10.1002/9780470478509.neubb002034

Quintana, D. S., Kemp, A. H., Alvares, G. A., & Guastella, A. J. (2013). A role for autonomic cardiac control in the effects of oxytocin on social behavior and psychiatric illness. *Frontiers in Neuroscience*, *7*, 48.

Radolf, L. S. (1977). The CES-D Scale A Self report Depression Scale for Research in the General Population. *Applied Psychological Measurement*, *1*(3), 385–401.

Ray, C. (1979). Examination stress and performance on a color-word interference test. *Perceptual and Motor Skills*, *49*(2), 400–402.

Reniers, R. L. E. P., Corcoran, R., Drake, R., Shryane, N. M., & Völlm, B. A. (2011). The QCAE: A Questionnaire of Cognitive and Affective Empathy. *Journal of Personality Assessment*, *93*(1), 84–95. https://doi.org/10.1080/00223891.2010.528484

Rouder, J. N., Morey, R. D., Morey, C. C., & Cowan, N. (2011). How to measure working memory capacity in the change detection paradigm. *Psychonomic Bulletin & Review*, *18*(2), 324–330. https://doi.org/10.3758/s13423-011-0055-3

Rumble, A. C., Van Lange, P. A. M., & Parks, C. D. (2010). The benefits of empathy: When empathy may sustain cooperation in social dilemmas. *European Journal of Social Psychology*, *40*, 856–866. https://doi.org/10.1002/ejsp.659

Russell, D. W. (1996). UCLA Loneliness Scale (Version 3): Reliability, Validity, and Factor Structure. *Journal of Personality Assessment*, *66*(1), 20–40. https://doi.org/10.1207/s15327752jpa6601_2

Salminen, T., Strobach, T., & Schubert, T. (2012). On the impacts of working memory training on executive functioning. *Frontiers in Human Neuroscience*, *6*. https://doi.org/10.3389/fnhum.2012.00166

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime: User's guide*.

Schulkin, J., McEwen, B. S., & Gold, P. W. (1994). Allostasis, amygdala, and anticipatory angst. *Neuroscience & Biobehavioral Reviews*, *18*(3), 385–396. https://doi.org/10.1016/0149-7634(94)90051-5

Seeman, T. E. (1996). Social ties and health: The benefits of social integration. *Annals of Epidemiology*, *6*(5), 442–451.

Simmons, W. K., & DeVille, D. C. (2017). Interoceptive contributions to healthy eating and obesity. *Current Opinion in Psychology*, *17*, 106–112. https://doi.org/10.1016/J.COPSYC.2017.07.001

Sklerov, M., Dayan, E., & Browner, N. (2019). Functional neuroimaging of the central autonomic network: Recent developments and clinical implications. *Clinical Autonomic Research*, *29*(6), 555–566. https://doi.org/10.1007/s10286-018-0577-0

Smith, R., Thayer, J. F., Khalsa, S. S., & Lane, R. D. (2017). The hierarchical basis of neurovisceral integration. *Neuroscience & Biobehavioral Reviews*, *75*, 274–296. https://doi.org/10.1016/J.NEUBIOREV.2017.02.003

Stevenson, R. J., Mahmut, M., & Rooney, K. (2015). Individual differences in the interoceptive states of hunger, fullness and thirst. *Appetite*, *95*, 44–57. https://doi.org/10.1016/J.APPET.2015.06.008

Stoet, G. (2010). PsyToolkit: A software package for programming psychological experiments using Linux. *Behavior Research Methods*, *42*(4), 1096–1104.

Stoet, G. (2017). PsyToolkit: A novel web-based method for running online questionnaires and reaction-time experiments. *Teaching of Psychology*, *44*(1), 24–31.

Strang, S., Hoeber, C., Uhl, O., Koletzko, B., Münte, T. F., Lehnert, H., Dolan, R. J., Schmid, S. M., & Park, S. Q. (2017). Impact of nutrition on social decision making. *Proceedings of the National Academy of Sciences*, *114*(25), 6510–6514.

Sun, M., Choi, E. Y., Magee, D. J., Stets, C. W., During, M. J., & Lin, E.-J. D. (2014). Metabolic Effects of Social Isolation in Adult C57BL/6 Mice. *International Scholarly Research Notices*, *2014*, 1–9. https://doi.org/10.1155/2014/690950

Tanaka Hirofumi, Monahan Kevin D, & Seals Douglas R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology*, *37*(1), 153–156. https://doi.org/10.1016/S0735-1097(00)01054-8

Tanaka, M., Ishii, A., & Watanabe, Y. (2014). Neural effect of mental fatigue on physical fatigue: A magnetoencephalography study. *Brain Research*, *1542*, 49–55. https://doi.org/10.1016/j.brainres.2013.10.018

Tanaka, M., & Watanabe, Y. (2012). Supraspinal regulation of physical fatigue. *Neuroscience & Biobehavioral Reviews*, *36*(1), 727–734. https://doi.org/10.1016/j.neubiorev.2011.10.004

Thayer, J. F. (2006). *ON THE IMPORTANCE OF INHIBITION: CENTRAL AND PERIPHERAL MANIFESTATIONS OF NONLINEAR INHIBITORY PROCESSES IN NEURAL SYSTEMS*. https://doi.org/10.2203/dose-response.004.01.002.Thayer

Thayer, J. F., & Lane, R. D. (2009a). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience & Biobehavioral Reviews*, *33*(2), 81–88. https://doi.org/10.1016/J.NEUBIOREV.2008.08.004

Thayer, J. F., & Lane, R. D. (2009b). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience & Biobehavioral Reviews*, *33*(2), 81–88. https://doi.org/10.1016/J.NEUBIOREV.2008.08.004

Thayer, J. F., & Sternberg, E. (2006). Beyond heart rate variability: Vagal regulation of allostatic systems. *Annals of the New York Academy of Sciences*, *1088*(1), 361–372. https://doi.org/10.1196/annals.1366.014

Tottenham, N., Tanaka, J. W., Leon, A. C., McCarry, T., Nurse, M., Hare, T. A., Marcus, D. J., Westerlund, A., Casey, B. J., & Nelson, C. (2009). The NimStim set of facial expressions: Judgments from untrained research participants. *Psychiatry Research*, *168*(3), 242–249.

Twenge, J., Baumeister, R., Tice, D., & Stucke, T. (2002). If you can't join them, beat them: Effects of social exclusion on aggressive behavior. *Journal of Personality and Social Psychology*, *81*, 1058–1069. https://doi.org/10.1037//0022-3514.81.6.1058

Twenge, J. M., Baumeister, R. F., DeWall, C. N., Ciarocco, N. J., & Bartels, J. M. (2007). Social exclusion decreases prosocial behavior. *Journal of Personality and Social Psychology*, *92*(1), 56.

Umberson, D. (1992). Gender, marital status and the social control of health behavior. *Social Science & Medicine*, *34*(8), 907–917.

van der Linden, D. (2011). The urge to stop: The cognitive and biological nature of acute mental fatigue. In P. L. Ackerman (Ed.), *Cognitive fatigue: Multidisciplinary perspectives on current research and future applications.* (pp. 149–164). American Psychological Association. https://doi.org/10.1037/12343-007

Wang, X., Wang, B.-R., Zhang, X.-J., Xu, Z., Ding, Y.-Q., & Ju, G. (2002). Evidences for vagus nerve in maintenance of immune balance and transmission of immune information from gut to brain in STM-infected rats. *World Journal of Gastroenterology*, *8*(3), 540–545. https://doi.org/10.3748/wjg.v8.i3.540

Watson, D., Clark, L. A., & Tellegen, A. (1988a). Development and Validation of Brief Measures of Positive and Negative Affect: The PANAS Scales. In *Journal of Personality and Social Psychology* (Vol. 54, Issue 6).

Watson, D., Clark, L. A., & Tellegen, A. (1988b). Development and Validation of Brief Measures of Positive and Negative Affect: The PANAS Scales. In *Journal of Personality and Social Psychology* (Vol. 54, Issue 6, pp. 1063–1070).

Wehrwein, E. A., Orer, H. S., & Barman, S. M. (2016). Overview of the anatomy, physiology, and pharmacology of the autonomic nervous system. *Regulation*, *37*(69), 125.

Whelan, R. (2008). Effective Analysis of Reaction Time Data. *The Psychological Record*, *58*(3), 475–482. https://doi.org/10.1007/BF03395630

Wickham, H. (2011). Ggplot2. *Wiley Interdisciplinary Reviews: Computational Statistics*, *3*(2), 180–185.

Williams, A. C., & Craig, K. D. (2016). Updating the definition of pain. *Pain*, *157*(11), 2420–2423. https://doi.org/10.1097/j.pain.0000000000000613

Williams, J. M. G., Mathews, A., & MacLeod, C. (1996). The emotional Stroop task and psychopathology. *Psychological Bulletin*, *120*(1), 3.

Wilson, R. S., Krueger, K. R., Arnold, S. E., Schneider, J. A., Kelly, J. F., Barnes, L. L., Tang, Y., & Bennett, D. A. (2007). Loneliness and risk of Alzheimer disease. *Archives of General Psychiatry*, *64*(2), 234–240.

Wilson, S. J., Woody, A., Padin, A. C., Lin, J., Malarkey, W. B., & Kiecolt-Glaser, J. K. (2019). Loneliness and Telomere Length: Immune and Parasympathetic Function in Associations With Accelerated Aging. *Annals of Behavioral Medicine*, *53*(6), 541–550. https://doi.org/10.1093/abm/kay064

Wirth, J. H. (2016). Methods for Investigating Social Exclusion. In P. Riva & J. Eck (Eds.), *Social Exclusion: Psychological Approaches to Understanding and Reducing Its Impact* (pp. 25–47). Springer International Publishing. https://doi.org/10.1007/978-3-319-33033-4_2

Wylie, G. R., Yao, B., Genova, H. M., Chen, M. H., & DeLuca, J. (2020). Using functional connectivity changes associated with cognitive fatigue to delineate a fatigue network. *Scientific Reports*, *10*(1), 21927. https://doi.org/10.1038/s41598-020-78768-3

Xu, Z., Adam, K. C. S., Fang, X., & Vogel, E. K. (2018). The reliability and stability of visual working memory capacity. *Behavior Research Methods*, *50*(2), 576–588. https://doi.org/10.3758/s13428-017-0886-6

Zhang, C., & Yu, X. (2010). Estimating mental fatigue based on electroencephalogram and heart rate variability. *Polish Journal of Medical Physics and Engineering*, *16*(2), 67–84. https://doi.org/10.2478/v10013-010-0007-7