Does a 2-week positive affect intervention facilitate physiological recovery from psychological stressors in young adults?

by

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Trait positive affect has been associated with a lower risk of cardiovascular disease (Boehm & Kubzansky, 2012). One pathway by which positive affect might influence physical health is by buffering against psychological stress and its physiological concomitants (*i.e.*, increases in heart rate and blood pressure). In fact, trait positive affect associates with more complete blood pressure recovery following a psychological stressor (DuPont et al., 2020). Prior work also suggests that increasing momentary positive affect in close proximity to a stressor accelerates cardiovascular and cortisol recovery following the task (*e.g.*, Kraft & Pressman, 2012; Speer & Delgado, 2017). However, no study to date has investigated whether increasing global positive affect – outside of the context of a stressor – can also alter stress physiology. As such, the current study aimed to test whether increasing global levels of positive affect with a 2-week positive psychological intervention would facilitate cardiovascular recovery from a psychological stressor in young adults. Prior to testing the study hypothesis, two pilot studies were conducted that aimed to validate a two-week positive psychological intervention (Study 1; N = 225) and a remote version of the Trier Social Stress Test (Study 2; N = 79; Kirschbaum, Pirke, & Hellhammer, 1993). Unfortunately, the two-week positive psychological intervention failed to increase positive affect in the intervention condition, precluding a test of the overall study hypothesis. In the second pilot study, the remote Trier Social Stress Test elicited emotional reactivity, but did not induce greater cardiovascular reactivity in the stress condition relative to a non-stressful control condition. As such, the final study (Study 3; N = 99) aimed to improve the remote Trier Social Stress Test. Results from the final study indicate that the remote Trier Social Stress Test successfully induced heart rate and blood pressure reactivity in the stress condition relative to controls. Furthermore, the task demonstrated good test-retest reliability when assessed one week later. Although the original study hypothesis could not be tested, developing, and validating an online stress task that can be administered remotely may allow future stress research to include populations that were previously unreachable.

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Acknowledgements

Throughout my dissertation, I challenged myself to create my own positive habits, just as I was asking from my participants. My morning ritual included walking my pup in downtown Pittsburgh, while I reflected on all of the people who I am grateful for and who, without their support, my academic and personal growth would not have been possible. Here are some of those reflections:

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1.0 Introduction

For decades, research on the relationship between mental and physical health has focused primarily on negative psychosocial factors that are encompassed by the broader construct of ill-being. Ill-being includes factors such as depressive symptoms, pessimism, hostility, neuroticism, or perceived stress. More recent research, however, has focused on positive psychosocial factors that are encompassed by the construct of well-being. (Pressman & Cohen, 2005; Steptoe, Dockray & Wardle, 2009; Boehm & Kubzansky, 2012; Howell et al., 2007; Veenhoven, 2008). Such factors may include happiness, optimism, spirituality, extraversion, or mastery (Sheldon, 2018). An incorrect assumption is that ill-being is simply the absence of well-being; however, ill-being and well-being can certainly co-occur (Aspinwall & Tedeschi, 2010). Moreover, ill-being and well-being do not consistently demonstrate inverse effects on the same outcome (*e.g.*, Heady, Holmstrom, & Wearing, 1985; Ryff et al., 2006), again suggesting that the presence of ill-being cannot be used to infer the absence of well-being (Aspinwall & Tedeschi, 2010). In line with these findings, well-being and ill-being have been proposed not only to impact different aspects of physical health, but also to influence health by distinct and potentially independent pathways (Ryff et al., 2006).

Perhaps one of the most well-studied aspects of well-being that may protect against disease risk is positive affect, which broadly refers to the experience of positive emotions (Pressman & Cohen, 2005; Steptoe, Dockray & Wardle, 2009). Although positive affect has been consistently associated with better health outcomes, the mechanisms by which positive affect influences health remain unclear. One possibility is that positive affect buffers against psychological stress and features of physiological stress responses (Cohen & Pressman 2005; Fredrickson et al., 2000). To elaborate, exaggerated, prolonged, and repeated physiological responses to acute stressors are believed to be a potential risk factor for poor health (Krantz & Manuck, 1984; Cohen, Janicki-Deverts, & Miller, 2007). In support of the hypothesis that positive affect may buffer against psychological stress, inducing acute increases in positive affect prior to a laboratory stress task facilitates the return of cardiovascular and cortisol parameters back to baseline levels (*e.g.,* Qin et al., 2019). Given that most of the work relating positive mood to stress physiology has used protocols to acutely prime a transient positive mood state before (Qin et al., 2019), during (Kraft & Pressman, 2012), or after a stress task (Fredrickson et al., 2000; Speer & Delgado, 2017), it is unclear whether these findings generalize to conditions where there is a sustained manipulation of mood states (e.g., over days as compared to minutes). Moreover, as mood states can span longer periods of time than have been studied in prior laboratory studies of stress reactivity, strategies for enhancing global positive affect may provide a useful tool for buffering against the cumulative and sustained effects of naturalistic stressors over time that could, potentially, impact physical health. Therefore, the current study investigates whether increasing positive affect with a two-week positive psychological intervention promotes cardiovascular recovery (heart rate and blood pressure) to an acute stressor.

1.1 Positive Affect as an Indicator of Well-being

Well-being is a broad construct that can be roughly divided into two components: eudaimonic and hedonic well-being (Ryff & Keyes, 1995; Keyes, Shmotkin & Ryff, 2002). Eudaimonic well-being is broadly thought to reflect a sense of fulfillment in life (Ryff & Keyes, 1995); however, there is debate about what specific constructs comprise eudaimonic well-being.

For example, Ryff and Keyes (1998) define eudaimonic well-being as an assemblage of six separate constructs including autonomy, personal growth, self-acceptance, life purpose, mastery, and positive relatedness. However, others have extended this definition of eudaimonic well-being to become a 'catch-all' term encompassing many psychological constructs, such as spirituality, self-discovery, and goal aspirations (reviewed in Ryan & Deci, 2001). Yet others suggest that eudaimonia is not a discrete psychological construct at all, but should instead be defined as behaviors that lead to a fulfilling life (Sheldon, 2018). A lack of consensus on constructs that comprise eudaimonic well-being has limited progress in understanding the role of eudaimonic well-being in physical health.

In contrast to eudaimonia, hedonic well-being has been more reliably operationalized by low negative affect, high positive affect, and life satisfaction (Diener et al., 1999). Hedonic well-being has been widely studied over the past fifty years (Diener et al., 1999), and its structure has been empirically supported by confirmatory factors analyses (*e.g.,* Gallagher, Lopez, and Preacher, 2009; Joshanloo et al., 2016). Although positive affect, negative affect, and life satisfaction are related constructs, they are assumed to be independent predictors of health (*e.g.,* Ryff et al., 2006; Ryff & Singer, 1998). Despite the notion that all three constructs (positive affect, negative affect, and life satisfaction) may impact health by distinct pathways, negative affect is by far the most frequently studied construct of hedonic well-being in relation to health outcomes (Seligman, 2008). As a consequence, the majority of behavioral interventions focus solely on reducing negative affect without impacting life satisfaction or positive affect. By focusing on only a single aspect of hedonic well-being – reducing negative affect – current behavioral interventions arguably provide an incomplete approach to treatment (Seligman, 2008). A more comprehensive behavioral intervention would include reducing negative affect while *simultaneously* increasing positive affect and life satisfaction. To address this issue, a so-called ‘fourth-wave’ of psychotherapy has emerged focusing on promoting well-being, with a particular focus on enhancing positive affect (Peteet, 2018). As it is assumed that positive affect, life satisfaction, and negative affect have discernable influences on health, psychotherapies that both reduce negative affect *and* increase positive affect and life satisfaction could have additive or synergistic effects on health outcomes. Therefore, understanding the potentially modifiable association between positive affect and subclinical risk factors or disease endpoints may lead to new behavioral interventions aimed at preventing and mitigating disease risk.

1.2 Positive Affect and Health

Positive affect is the general experience of positive emotions. In contrast to focusing on any one positive emotion, positive affect provides a snapshot of the overall experience of positively valanced emotions within a given time frame. Two meaningful time frames used in psychological research are trait and state positive affect. Trait positive affect refers to the dispositional tendency to experience positive emotions *in general* (or at least for more than a few weeks; see Pressman & Cohen, 2005), while state positive affect reflects the momentary experience of positive emotions. The benefit to studying trait positive affect is that it reflects the *cumulative* experience of various positive emotions rather than focusing on any particular and potentially short-lived positive emotion, such as joy, contentment, or excitement (Watson, 2000). If positive affect influences physical health, it is likely that an accumulation of positive experiences and corresponding emotions may be more meaningful than any particular positive emotion experienced in isolation (Watson, 2000; Pressman & Cohen, 2005; Dockray & Steptoe, 2010).

In support of this notion, trait positive affect has been associated with lower disease risk, especially with respect to cardiovascular and cardiometabolic diseases. Prospective studies, for example, demonstrate that high positive affect associates with a 20% reduced risk for stroke and coronary heart disease in healthy populations (Ostir et al., 2001; Davidson, Mostofsky, & Whang, 2010; but also see Nabi et al., 2008) and 4% reduction of stroke in patients with hypertension (Agewall, Wilkstrand, & Fagerberg, 1998). Positive affect has also been associated with a 12% aggregated risk reduction for myocardial infarction - even after controlling for traditional risk factors (Hawkins et al., 2014). In addition to reduced disease risk, greater positive affect associates with prolonged survival (Denollet et al., 2008; Brummett et al., 2005; Barefoot et al., 2000; Hoen et al., 2013; Sajjad et al., 2017; but also see van der Vlugt et al., 2005) and fewer re-hospitalizations in cardiac patients (Middleton & Byrd, 1996). If positive affect is indeed implicated in disease pathology, it may also relate to subclinical markers of disease and risk factors for disease. To date, only a single study demonstrates that higher positive affect prospectively associates with less coronary artery calcification (Kroenke et al., 2012), limiting insight into whether positive affect may influence subclinical disease processes and correlated risk factors.

In addition to disease outcomes, positive affect also relates to cardiovascular function in daily life that may be indicative of better health and lower risk for disease (*e.g.,* Hillebrand et al., 2013; Conen & Bamberg, 2008; Zhang, Wang, & Li, 2016). Ambulatory assessments that allow for concurrent measures of cardiovascular parameters and affect consistently demonstrate an association between greater positive affect and lower heart rate throughout the day (Ilies, Dimotakis, & Watson, 2010; Steptoe & Wardle, 2005; Steptoe, Wardle, & Marmot, 2005); although this may be more pronounced in men than in women (Steptoe & Wardle, 2005; Steptoe, Wardle, & Marmot, 2005). By contrast, positive affect is less consistently associated with blood pressure. Single item ratings of happiness have been related to lower diastolic blood pressure during sleep (Shapiro, Jamner, & Goldstein, 1997), and lower systolic blood pressure during the day (Steptoe & Wardle, 2005). However, other studies have failed to replicate these findings, (Steptoe, Wardle & Marmot, 2005; Ilies, Dimotakis, & Watson, 2010) and suggest that negative affect is more closely associated with resting blood pressure than positive affect (Ilies, Dimotakis, & Watson, 2010). An additional indicator of cardiovascular function is heart rate variability. Heart rate variability – particularly occurring at typical breathing rates – indirectly reflects autonomic (*i.e.*, parasympathetic) activity at the level of the heart, with greater heart rate variability consistently conferring reduced risk for cardiovascular events (Hillebrant et al., 2013). Self-reported positive affect has been associated with higher heart rate variability throughout the day (Bhattacharyya et al., 2008; Schwerdtfeger et al., 2014; Schwerdtfeger et al., 2015; Zhenhong, Lü, & Qin, 2013; but also see Sloan et al., 2017).

In addition to basal cardiovascular function, positive affect is also linked with cortisol rhythms throughout the day. Cortisol exhibits a diurnal rhythm that peaks within the first 30 minutes of waking and steadily declines during the day. More positive health outcomes have been associated with a cortisol pattern typified by a relatively large increase in cortisol upon awakening and a steeper decline throughout the day, which presumably reflects overall cortisol output across the day. Consistent with this interpretation, a flatter cortisol slope has been associated with greater coronary artery calcification (Matthews et al., 2006; Hajat et al., 2013), and endothelial dysfunction (Hajat et al., 2013). Positive affect is linked with steeper diurnal cortisol slopes (Miller et al., 2016; Hoyt et al., 2015; Polk et al., 2005; but also see Brummett et al., 2009) and less total cortisol output during the day (Lai et al., 2005; Steptoe, Wardle & Marmot, 2005). In view of existing evidence, it is plausible that positive affect may relate to health via direct or indirect pathways that alter cardiovascular and neuroendocrine function (Pressman & Cohen, 2005).

1.3 Direct Pathways: Health Behaviors

Positive affect may directly impact health through a number of behavioral and psychological pathways, such as promoting health behaviors and enhancing social functioning. Both trait and state positive affect are generally believed to increase behaviors that improve health and reduce behaviors that negatively impact health. One such health behavior, physical activity, is consistently associated with greater positive affect. Although most studies investigate the influence of physical activity on enhancing positive affect (Reed & Ones, 2006), there is some evidence that this relationship may be bidirectional (*e.g.*, Kim et al., 2017). For example, longitudinal studies suggest that higher trait positive affect associates with increased physical activity at two to five years follow-up in healthy (Baruth et al., 2011) and patient populations (Sin, Moskowitz, & Whooley, 2015). Cross-sectional studies consistently demonstrate a relationship between positive affect and more physical activity (Watson, 1988; Watson, 2000; Pasco et al., 2011; Cameron, Bertenshaw, & Sheeran, 2017), which is independent of negative affect (Pasco et al., 2011). Therefore, current evidence is consistent with the interpretation that positive affect may benefit health by increased physical activity.

In addition to physical activity, positive affect may also impact health by its influence on sleep quality or quantity (sleep duration). A recent review provided preliminary evidence for an association between higher positive affect, better subjective sleep quality, and fewer reported insomnia symptoms (Ong et al., 2017). However, these findings were specific to self-reported measures of sleep quality, while behaviorally assessed sleep quality was uncorrelated with positive affect (von Kanel et al., 2014). Positive affect is also largely unrelated to sleep duration (Fredrickson et al., 2008; Kalak et al., 2014; Ong et al., 2017), especially after adjusting for negative affect or perceived stress (Galambos, Dalton, & Maggs, 2009). These findings parallel those demonstrating that individuals high in positive affect self-report better physical health, regardless of objective measures of physical health (*e.g.,* Pettit et al., 2001). In a similar vein, those high in positive affect may be less likely to report or identify sleep disturbances compared to their less positive counterparts. Importantly, subjective sleep quality has been linked to a host of negative health outcomes, including hypertension (Wang et al., 2017), poor endothelial function, and arterial stiffness (Aziz et al., 2017), suggesting that positive affect may still impact health by promoting subjective experiences of sleep.

Yet another pathway through which positive affect may alter health is by substance use, such as cigarette smoking and alcohol consumption. Positive affect has been linked with a reduced likelihood of smoking in the future (Lappan et al., 2020; Sin, Moskowitz, & Whooley, 2015), and better maintenance of smoking cessation (Leventhal et al., 2008; but also see Heffner et al., 2018). Similarly, inducing positive affect by presenting pleasant photographs reduces craving for cigarettes in smokers (Shiffman et al., 2013). Based on available evidence, there appears to be a relationship between higher positive affect and reduced cigarette smoking and cravings in current smokers. In contrast to cigarette smoking, there is mixed evidence on the effects of positive affect on alcohol consumption. Trait positive affect fails to associate with either the frequency or quantity of alcohol consumption two years later in college freshman (Molnar et al., 2009). However, state markers of positive affect associate with drinking *more* alcohol in both heavy drinkers (Bresin & Fairbairn, 2019) and a community sample (Duif et al., 2020). In terms of its impact on substance use, positive affect may exert opposing influences on health by reducing cigarette smoking, while potentially increasing alcohol consumption.

A final domain of health behaviors that may be influenced by positive affect is food consumption patterns. Although longitudinal data is lacking in this area, cross-sectional research indicates that trait positive affect correlates with a higher intake of fruits, vegetables, (White et al., 2013; Warner et al., 2017) legumes, and nuts (Ford et al., 2013). In contrast, negative affect appears to be associated with consuming greater amounts of fast food and sweets (Ford et al., 2013). However, it is unclear whether the associations between affect and eating behavior translates to adiposity or obesity. For example, positive affect does not predict changes in adiposity across time (Shirom et al., 2012). Similarly, controlling for negative affect eliminates cross-sectional relationships between adiposity and positive affect, suggesting that negative affect is more robustly associated with adiposity than positive affect (Pasco et al., 2013; Carr, Friedman, & Jaffe, 2007). To date, there remains insufficient data to suggest that positive affect may impact health by altering diet or subsequently impacting adiposity or risk for obesity.

In summary, positive affect may influence health by behaviors that promote health. The health behaviors that are most likely to be related to higher positive affect are greater physical activity, increased subjective sleep quality, and reduced cigarette smoking or smoking cessation. Of note, it is possible that in some instances, positive affect may also promote poor health behaviors via greater alcohol use.

1.4 Direct Pathways: Social Processes

In addition to health behaviors, positive affect may also relate to physical health via social processes. There are various discernable social processes that have been associated with health outcomes, including social integration, loneliness, and perceived social support. Social integration is defined as participating in and belonging to a multitude of meaningful social networks. Social integration is often measured by quantifying the number of social roles one holds and size of their social network within each role for a given individual. Social integration can be measured continuously or dichotomously. Continuous measurements of social integration allow for the investigation of dose-response relationships between the size of social networks and number of various social roles for a given outcome. Dichotomous scales of social integration categorize people as either socially isolated or socially connected. Social isolation is typically classified as reporting few social roles or a small network (Cohen & Janicki-Deverts, 2009). Importantly, continuous and dichotomous measures of social networks appear to have distinct pathways by which social integration may influence health and health behaviors (*e.g.*, Chin & Cohen, 2020).

In contrast to social integration, loneliness is *perceived* social isolation or a lack of meaningful social relationships. Because loneliness is subjective, one can be lonely despite reporting a large social network or involvement in a wide variety of social roles if they perceive poor relationship quality within these networks (Hawkley & Cacioppo, 2010). Loneliness is therefore measured by self-reported dissatisfaction with social relationships. The final social process of interest is perceived social support, or the belief that one's social network(s) can facilitate coping in response to a negative event (Uchino, Cacioppo, & Kiecolt-Glaser, 1996). Importantly, perceived social support is independent of whether social support is either requested or received. In fact, perceived social support is only modestly correlated with receiving social support (*r* ~ 0.35; Haber et al., 2007).

Of the social processes mentioned, social integration appears to have the most consistent associations with health (Cohen & Janicki-Deverts, 2009). Smaller social networks associate with greater cardiovascular events (Valtorta et al., 2016; Chin & Cohen, 2020), mortality (Chin & Cohen, 2020; Yu et al., 2019), and disease progression (Chin & Cohen, 2020). Similarly, loneliness has been associated with an increased risk for coronary heart disease (Eaker et al., 1992; Thurston & Kubzansky, 2009), but not mortality (Yu et al., 2020). Finally, perceived social support is associated with longevity (Shor, Roelfs, & Yogev, 2013; Barth, Schneider, & Von Kanel, 2010), and less cardiovascular risk factors (Seeman et al., 2014), but evidence remains limited in its association with cardiovascular events (Freeborne et al., 2019; Barth, Schneider, & Von Kanel, 2010). Taken together, social integration and loneliness appear to be social processes most likely to influence cardiovascular disease risk. As such, positive affect may influence health by facilitating the development or maintenance of social networks, increasing the number of social roles, or protecting against loneliness.

The integration of affective and social processes is a recent topic of interest (*e.g.,* Uchino & Eisenberg, 2019), as both processes are hypothesized to influence health through similar mechanisms (Smith, Baucom, 2017; Smith & Weihs, 2019). Unfortunately, affective and social factors are rarely studied together and when they are, directionality is often not assessed. In studies testing unidirectional relationships between affect and social factors, positive affect has been associated with perceived social connectedness (Waugh & Fredrickson, 2003), greater social support (Staw, Sutton, & Pelled, 1994; Baldassare et al., 1984), and larger social networks (Requena, 1995; Lee & Ishii-Kuntz, 1987). Social interactions are also believed to enhance positive affect as facilitating social reactions between strangers leads to increases in positive affect (McIntyre et al., 1991; McIntyre et al., 1990; Vittengl & Holt, 2000). Along similar lines, individuals who are socially integrated report higher positive affect independent of their daily interactions with others. By comparison, less social integration associates with increases in positive affect that depend on the frequency of daily social interactions (Cohen & Lemay, 2007). Although a bidirectional relationship between positive affect and better social functioning has been hypothesized (Ramsey & Gentzler, 2015), this association has not yet been robustly tested. As such, the relationship between positive affect and social processes (*e.g.*, social integration, loneliness, and perceived stress) likely have additive or synergistic effects on health.

1.5 The Indirect Pathway: Psychological Stress and Health

In addition to its relationships to health behaviors and social factors, positive affect may also relate to health by buffering against the effects of psychological stress and its physiological concomitants. During moments of perceived psychological stress, the sympathetic adrenal medullary (SAM) system becomes activated for most individuals, leading to rapid increases in heart rate and blood pressure (McEwen, 1998; Benarroch, 2005; Sapolsky, Romero, & Munck, 2000). Aspects of these cardiovascular adjustments (*e.g.*, rises in blood pressure) are believed to increase turbulent blood flow at some arterial sites that may accumulate over time to initiate or exacerbate endothelial damage and ensuing atherogenic phenomena (Jennings et al., 2004). In addition to its effects on the heart and vasculature, the sympathetic nervous system also stimulates the production of pro-inflammatory cytokines (Bierhaus et al., 2003; Marsland et al., 2017), that may further impact the immune cascade that contributes to the progression of atherosclerosis (Gu, Tang, & Yang, 2012). The cardiovascular reactivity hypothesis postulates that reactions to stressors that are prolonged, repeated, or of large magnitude can enhance risk for cardiovascular disease (Krantz & Manuck, 1984; Cohen, Janicki-Deverts, & Miller, 2007).

In line with this hypothesis, studies in non-human primates demonstrated that greater heart rate reactivity to handling stress associated with higher atherosclerosis in the coronary arteries (Manuck, Kaplan, & Clarkson, 1983; Manuck et al., 1989). Similarly, studies in humans find that greater blood pressure reactivity associates with both concurrent (Kamarck et al., 1997; Gianaros et al., 2002; Spartano et al., 2014; Brindle et al., 2018; DuPont et al., 2020) and prospective development of atherosclerosis (Barnett et al., 1997; Jennings et al., 2004; Heponiemi et al., 2007; Low, Salomon, & Matthews, 2009), even after controlling for traditional risk factors. Most recently, this work has been extended to show that ambulatory blood pressure responses to task strain or social conflict also associates with preclinical atherosclerosis (Kamarck et al., 2018). Thus, cardiovascular (heart rate and blood pressure) reactivity may serve as a physiological pathway by which positive affect can influence cardiovascular disease risk. A single study that has investigated the relationship between affect, cardiovascular reactivity and preclinical atherosclerosis suggested that positive affect was related to heart rate, but not blood pressure reactivity. Importantly, heart rate reactivity was unrelated to preclinical atherosclerosis, potentially suggesting that positive affect may not influence health by the initial cardiovascular responses that occur in the presence of a psychological stressor (DuPont et al., 2020).

In addition to the SAM system, the hypothalamic-adrenal-medullary (HPA) axis also becomes engaged during psychological stressors that include social evaluation (Dickerson & Kemeny, 2004). When the HPA axis becomes engaged, corticotrophin releasing hormone (CRH) is released from the hypothalamus. CRH has two functions important for physiological responses to stress. First, CRH facilitates neuronal activation of the SAM system, by enhancing catecholamine release and further facilitating SAM-evoked increases in heart rate and blood pressure (Vale et al., 1983; Sapolsky, Romero, & Munck, 2000). As its second function, CRH signals the release of adrenocorticotropic hormone (ACTH) from the pituitary that then stimulates the production of cortisol from the adrenal cortex (Sapolsky, Romero, & Munck, 2000). Circulating cortisol can also impact heart rate and blood pressure during stress by enhancing the sensitivity to and facilitate binding of catecholamines on cardiac and vascular tissues (Sakaue & Hoffman, 1991; Collins, Caron, & Lefkowitz, 1988; Sapolsky, Romero, & Munck, 2000). In contrast to the effects of cortisol facilitating the effects of SAM on the cardiovascular system, cortisol suppresses SAM-evoked activation of pro-inflammatory cytokines (Padgett & Glaser, 2003).

In contrast to cardiovascular responses to stress, it is slightly less clear how cortisol responses to stress may be implicated in cardiovascular disease risk. It is plausible that heightened and sustained cortisol release can facilitate sheer stress and endothelial damage by its effects on the cardiovascular system (Sapolsky, Romero, & Munck, 2000). By contrast, cortisol may also provide beneficial effects by reducing systemic inflammation that could, in turn, protect against atherogenesis (Padgett & Glaser, 2003). Initial reports suggest that cortisol responses to acute psychological stressors associates with future hypertension risk (Hamer & Steptoe, 2012) and greater calcification at the carotid artery (Hamer et al., 2012). Of note, although cortisol and cardiovascular responses to stress are modestly correlated (r = 0.29 to 0.39; Cohen et al., 2000), individuals who display exaggerated blood pressure reactivity do not necessarily have larger cortisol responses to stress (Hamer et al., 2012). This might suggest that SAM system and HPA axis may represent dissociable pathways by which psychological stress may influence health across individuals.

Individual differences in cardiovascular and endocrine responses to psychological stressors can be assessed by laboratory paradigms. Laboratory stress tasks allow for rigorous experimental control of stressor stimuli and simultaneous collection of multiple physiological markers. Physiological responses to stress are often partitioned into two parameters: reactivity and recovery. Stress reactivity is defined as the magnitude of the response elicited by the stressor and is often assessed by comparing physiological levels at baseline to task levels (*e.g.*, 5mmHg increase in blood pressure; Linden et al., 1997; Llabre et al., 1991). Stress recovery represents the return to baseline levels, although the method of assessment is less standardized for this parameter (Linden et al., 1997). Both stress reactivity and recovery to laboratory stressors exhibit good test re-test reliability (Christenfeld, Glynn, & Gerin, 2000; Manuck et al., 1993; Kamarck, Jennings, & Manuck, 1992; Kamarck et al., 1994). Given the high intraindividual stability, stress responses have been hypothesized to represent dispositional tendencies or phenotypes (Manuck et al., 1993; Kamarck, Jennings, & Manuck, 1992; Kamarck et al., 1994). Along these lines, physiological reactivity measured in the laboratory is correlated with ambulatory assessments of stress reactivity in daily life (Gregg, Matyas, & James, 2005; Kamarck, Debski, & Manuck, 2000); although studies have not yet tested whether this extends to measures of recovery. Importantly, laboratory assessed reactivity and recovery represent phenotypical responses to stress, but does not provide information about daily stress exposure (Krantz & Manuck, 1984). In other words, high reactors may be protected against the potential negative consequences of physiological stress if they are in less stressful environments or can implement strategies that would result in less frequent activation of the stress response. Thus, positive affect may influence disease risk, in part, by its ability to act on physiological reactivity and/or recovery.

1.6 Positive Affect and Psychological Stress

Positive affect may mitigate physiological damage in response to psychological stress by either reducing the magnitude of the response (*i.e.,* reactivity), or facilitating the return to baseline after the stressor (*i.e.,* recovery). The broaden and build theory postulates that positive emotions facilitate physiological recovery, but not reactivity, to psychological stressors (Fredrickson et al., 2000). In support of this theory, four lines of research demonstrate a relationship between positive affect and more complete cortisol and/or cardiovascular recovery to stress.

First, rodent models have been used to test whether receiving rewards can influence physiological responses to stress. Although positive affect cannot be directly assessed in rodents, delivering primary rewards, such as sucrose, or enriching home cage environments with toys may reasonably elicit pleasurable experiences. Typically, these pleasurable experiences (sucrose and environmental enrichment) are delivered for a few weeks leading up to a stressful event. Sucrose consumption and environmental enrichment both result in reduced cortisol responses to stressors (Ulrich-Lai et al., 2010; Ulrich-Lai et al., 2007; Belz et al., 2003; Francis et al., 2002). One study also found that sucrose consumption led to reduced heart rate responses to restraint stress, suggesting that the effects of positive affect may influence both SAM and HPA pathways (Ulrich-Lai et al., 2010). Importantly, animal paradigms fail to evaluate cardiovascular recovery to stressors, making it difficult to know whether pleasurable experiences may facilitate the return of physiological parameters to baseline values. Despite this limitation, the evidence suggests a relationship between pleasant experiences and reduced cortisol and cardiovascular responses to stressors in animal models.

The second line of work capitalizes on individual differences in emotional reactions to acute stressors. During stress, positive affect typically decreases while negative affect increases (*e.g.,* Papousek et al., 2010); however, the magnitude of these changes differs across individuals. It would therefore be expected that individuals who report smaller reductions in positive affect during a stressor may be protected from its physiological consequences. Consistent with this reasoning, smaller reductions in state positive affect during a stressor associates with faster cortisol (Waugh et al., 2012) and cardiovascular (Tugade & Fredrickson, 2004; Dowd, Zautra, & Hogan, 2010) recovery following the stressor. Interestingly, changes in state positive affect are no longer associated with cardiovascular recovery after controlling for *trait* positive affect. Therefore, trait positive affect may be more strongly correlated with stress physiology, which is discussed in greater detail below (Papousek et al., 2010; see 'How Might Positive Affect Buffer Against Stress' below).

The third line of evidence includes mood manipulation studies when positive affect is experimentally induced within the context of a psychological stressor. Positive affect has been induced by recalling autobiographical memories (Speer & Delgado, 2017), using Duchenne smiles (Kraft & Pressman, 2012), and showing film clips (Fredrickson et al., 2000), pictures (Qin et al., 2019), or erotic images (Cresswell et al., 2013). Despite the method used to enhance positive affect, participants in the intervention condition, again, demonstrate faster cardiovascular (Kraft & Pressman, 2012; Fredrickson et al., 2000; Qin et al., 2019) and cortisol (Speer & Delgado, 2017; Cresswell et al., 2013) recovery after stress.

Finally, the relationship between *trait* markers of positive affect have also been linked to faster blood pressure recovery to laboratory stressors in a recent meta-analysis (DuPont et al., 2020). Unfortunately, there were only two studies that measured cortisol responses to stress. One of those studies reported that trait positive affect was associated with faster cortisol recovery (r = -0.22; Bostock et al., 2011), while the second studies reported null associations (Mendoca de Souza et al., 2007). Because there were only two studies measuring cortisol, meta-regression analyses were precluded making it difficult to understand whether trait positive affect accelerates cortisol recovery under specific conditions (*e.g.,* social vs cognitive stressors) or within certain demographics (*e.g.,* men vs women, younger vs older). Despite these limitations, a clear pattern has emerged across various lines of evidence that link both state and trait positive affect with faster cortisol and cardiovascular recovery to psychological stressors. Given the relationship between positive affect and stress physiology, it is important to consider *how* positive affect might influence various stress-related processes.

1.7 How Might Positive Affect Buffer Against Stress

As noted above, trait positive affect is more strongly correlated with physiological recovery compared to state positive affect. This may suggest that positive emotions, themselves, cannot fully explain how positive affect buffers against stress. Instead, individuals high in trait positive affect may possess behavioral and/or psychological resources that then reduce psychological stress at various stages of the process (Figure 1). In the initial stage, negative events must be attended to and perceived as stressful (Figure 1; pathway a). If the event is perceived as stressful, then coping strategies may be implemented to reduce the emotional and physiological responses to the event

(Figure 1; pathway b). After the stressor is removed, rumination about the stressor can further sustain emotional and physiological responses to the stressor (Figure 1; pathway c). Individuals high in trait positive affect may therefore implement more adaptive strategies across the various stages of the stress process (*i.e.*, attention to and perception of stressors, coping, and rumination) that may encourage physiological recovery.

At the first stage of the stress process, individuals must first attend to potentially stressful events or situations. Therefore, trait positive affect may influence attention either towards positively valanced stimuli and/or away from negatively valanced stimuli. In general, a positivity bias exists in the general population and is believed to occur at levels below conscious processing (Pool et al., 2016). Furthermore, those high in trait positive affect appear to have heightened attention towards positively valanced stimuli relative to neural stimuli (Raila, Scholl, & Gruber, 2015; Grafton & MacLeod, 2017). Similarly, inducing state positive affect has also been shown to strengthen biases towards positively valanced stimuli (Tamir & Robinson, 2007; Wadlinger & Isaacowitz, 2006). A major limitation of this work is that no studies have incorporated presentations of negatively valanced stimuli, making it unclear whether trait positive affect biases attention *away from* negative stimuli. If trait positive affect redirects attention away from negative stimuli, then those high in trait positive affect may be less exposed to stressors, regardless of their phenotypic stress response. In this way, trait positive affect may protect against the occurrence of acute episodes of psychological stress above what can be measured with laboratory stress paradigms.

After attending to a negative event or stimulus, it must then be perceived as stressful. Cross-sectional studies indicate that trait positive affect associates with lower reports perceived stress (Horiuchi et al., 2018; Schiffrin & Nelson, 2010; Civitci, 2015). Similarly, students high in trait positive affect are less likely to report experiencing academic stress, even after controlling for trait negative affect and state measures of positive and negative affect (Papousek et al., 2010; but also see Watson, 1988). Experimental manipulation of positive affect also appears to change how negative information is perceived. For example, one study had participants take a (bogus) questionnaire to assess social abilities. Following a mood induction, participants were provided feedback on their social abilities, but the participants had to select whether they wanted feedback on their social strengths or social weaknesses. Participants in the positive mood induction were more likely to ask about their social weaknesses than those who received a negative mood induction (Trope & Neter, 1994). One potential explanation for these seemingly counterintuitive findings is that negative, self-relevant information is perceived as less threatening or stressful during moments of high positive affect. In other words, trait and state positive affect may bias interpretations of negative events as less stressful, which could further influence downstream physiological reactivity to negative events.

Even if individuals high in trait positive affect identify a negative event and perceive it as stressful, they may engage coping strategies to manage their negative reactions to the stressor. Negative reactions can be managed by either approach or avoidance coping strategies. Approach coping reduces distress by engaging in the stressful event, while avoidance coping includes disengaging with the stressor (Endler & Parker, 1990; Suls & Fletcher, 1985; Tobin, Holroyd, Reynolds, & Wigal, 1989). Although coping strategies cannot be neatly divided into 'adaptive' or 'maladaptive' without considering context (Carver, Scheier, & Weintraub, 1989), approach coping is typically considered to be more useful. Approach coping includes both emotion-focused coping that intervenes on the emotional reactions to the stressor (*e.g.*, seeking emotional support or using humor), and problem-focused coping that intervenes on aspects of the stressor (*e.g.*, seeking instrumental support, or planning; Lazarus & Folkman, 1984). Individuals high in trait positive affect are more likely to engage in both emotion-focused and problem-focused coping strategies compared to those low in trait positive affect (Ben-Zur, 2009; Chartier, Gaudreau, & Facteau, 2010). In addition, momentary assessment of concurrent state positive affect and coping suggests that greater state positive affect associates with an increased likelihood of using problem-focused coping strategies during stress (Pavani et al., 2016). It is therefore reasonable to postulate that both trait and state positive affect may act as psychological resources and make it easier to utilize more adaptive coping strategies.

As a final stage of the stress response, ruminating after a stressful event may lead to prolonged activation of stressor-evoked physiology well after the stressor is removed (Ottaviani et al., 2016). Although positive affect correlates with reduced rumination, this may be more closely linked to negative affect rather than positive affect (Pavani et al., 2016) Although rumination is colloquially defined as repetitive *negative* thoughts about a past event, it is also possible to have *positive* ruminations. A positive rumination may be self-focused (*e.g.*, "I think I performed well on that difficult task"), or emotion-focused (*e.g.*, "I feel so much better now that I finished my test"). Evidence suggests that trait positive affect is associated with more frequent positive ruminations following positive events (Hamilton et al., 2017; Harding, Hudson, & Mezulis, 2014); however, research is limited into whether this extends to negative events. For example, trait positive affect may provide a more constructive interpretation of a stressful event in an attempt to increase positive affect to pre-stressor levels. Rumination following a stressor may be the most important psychological resource to explain how positive affect facilitates physiological recovery, as both processes occur after the stressor has been removed.

1.8 Enhancing Positive Affect

As positive affect may influence health through a variety of mechanisms, the ability to modify positive affect could have important implications for behavioral interventions aimed at preventing and/or mitigating disease risk. Positive affect is proposed to be influenced by three main factors: genetics, life circumstances, and intentional activities (Lyubomirsky, Sheldon, & Schkade, 2005). As only intentional activities are easily modified, it is crucial to characterize the relative contribution of each factor in determining positive affect to assess whether positive affect is a worthwhile focus of behavioral intervention.

Initial studies attributed individual differences in positive affect largely to genetic factors, concluding that positive affect was unable to modified. In these initial studies, the heritability of positive affect was estimated by comparing levels of well-being between monozygotic and dizygotic twins. Personality measures of well-being were assessed in both twins at two times points, either 4.5 or 10 years apart (Lykken & Tellegen, 1996). The within-person correlation between well-being at baseline and follow-up were moderate (*r* ~ 0.50) and was referred to as the stable component of well-being (Lykken & Tellegen, 1996; Nes et al., 2006; McGue et al., 1993). Genetic factors were estimated to account for 80 – 95% of the variance in the stable component of well-being (Lykken & Tellegen, 1996) and have since been replicated (McGue et al., 1993) and extended to include measures of hedonic well-being (Nes et al., 2006). The authors concluded that individual differences in the stable component of well-being reflected a hedonic setpoint, or a baseline level of well-being that is genetically predetermined (Lykken & Tellegen, 1996).

However, the stable component of well-being does not account for prolonged fluctuations around the setpoint that may happen at any given time. For example, two recent meta-analyses found that cross-sectional assessments of hedonic well-being were 22-41% heritable (Nes &

Røysamb, 2015; Bartels, 2015). After considering the measurement error of self-report questionnaires, the upper estimate for heritability of general subjective well-being at any point in time is estimated to be around 50% (Nes & Røysamb, 2015). Taken together, these studies suggest that a hedonic set point might exist and that it is heritable, but that other factors still influence fluctuations in positive affect around that setpoint at any given time (Nes & Røysamb, 2015).

If the hedonic setpoint is stable and unlikely to be modified, it is important to consider other factors that may impact fluctuations in positive affect, such as life circumstances. Life circumstances can include a broad range of events, characteristics, and external influences including age, gender, culture, religion, socioeconomic status, and various life events (*e.g.*, becoming unemployed, getting married, or purchasing a new home). Basic demographic factors have been found to explain only a small portion (8 – 20%) of the variance in overall happiness (Campbell, Converse, & Rodgers, 1976; Andrews & Withey, 2012; Argyle, 2003). Furthermore, life circumstances are more likely to impact cognitive appraisals of life satisfaction, while only exhibiting modest effects on positive or negative affect (reviewed in Luhmann et al., 2012). Even when life events do enhance positive affect, these gains in positive affect fail to persist for an extended period of time, a phenomenon known as hedonic adaptation (reviewed in Lyubomirsky, 2010). Hedonic adaptation is the notion that positive affect quickly returns to baseline levels following positive events and that smaller increases in positive affect occur after repeated exposure to the same event (Diener, Lucas, & Scollon, 2009). In line with the above evidence, some aspects of life circumstances are difficult to modify (*e.g.*, age, sex, race), and the circumstances that *can* be modified have modest and short-lived influences on positive affect (Luhmann et al., 2012).

In summarizing these findings, Lyubomirsky and colleagues (2005) presented the happiness pie chart, which roughly estimates the variance in happiness that can be attributed to various factors. According to the happiness pie chart, genetic and life circumstances are estimated to account for 50% and 10% of subjective well-being, respectively, while the remaining 40% is proposed to be due to cognitive and behavioral strategies, or so-called intentional activities (Lyubomirsky, Sheldon, & Schkade, 2005). Although the happiness pie chart has been criticized for being too simplistic (Brown & Rohrer, 2019), it has successfully challenged the expectation that positive affect is unable to be modified (Sheldon & Lyubomirsky, 2019). As a result, researchers were given an empirical basis to create positive psychological interventions intended to increase positive affect around a given setpoint (Sheldon & Lyubomirsky, 2019).

Positive psychological interventions are designed to alter cognitive, behavioral, and/or motivational resources with the goal of increasing the duration, intensity, or frequency of positive emotions (Lyubomirsky & Layous, 2013). This definition spans a large range of interventions, including mindfulness training, utilizing signature strengths, imagining your best self, and practicing gratitude. Although implementing these interventions did not increase happiness by the hypothesized 40% (Lyubomirsky, Sheldon, & Schkade, 2005), positive psychological interventions do provide a measurable impact on positive affect, anxiety, and depression. Two meta-analyses concluded that positive psychological interventions result in small-to-moderate increases in positive affect (d = 0.35-0.45; Boiler et al., 2013; Sin & Lyubomirsky, 2009) that are maintained for at least three-to-six months (d = 0.22; Boiler et al., 2013). However, studies implementing longer follow-ups are necessary to test the long-term benefits of positive psychological interventions. Importantly, these meta-analyses aggregated across various types of positive psychological interventions, making it unclear which intervention(s) provide the largest gains in positive affect. Overall, this initial evidence is supportive of using positive psychological interventions to enhance positive affect.

1.9 Positive Psychological Interventions and Health

As positive psychological interventions are now established for enhancing positive affect, emerging research is testing the utility of these interventions for encouraging healthy behaviors and improving physical health. So far, positive psychological interventions show promise for improving subjective sleep quality (Jackowska et al., 2016), increasing physical activity (Celano et al., 2018a; Celano et al., 2018b; Peterson et al., 2012), and facilitating adherence to both low-sodium diets and medication (Celano et al., 2018b). Notably, the effects of positive psychological interventions on physical activity are maintained at one-year follow-up (Peterson et al., 2012). In addition to health behaviors, positive psychological interventions have had initial success at reducing pro-inflammatory cytokines (Nikrahan et al., 2016) and lowering ambulatory assessments of blood pressure (Jackowska et al., 2016). The effects of positive psychological interventions on cortisol remains unclear, with a single study suggesting that such interventions may lead to a smaller cortisol awakening response in coronary patients (Nikrahan et al., 2016); however, this finding was not replicated in a second sample of healthy adults (Jackowska et al., 2016). An initial study demonstrated that cardiac patients who completed a positive psychological intervention had a lower risk for future cardiac events than patients in an active control condition (Peterson et al., 2012). Although this new field supports the potential utility of positive psychological interventions in medical settings, much research is still needed to understand which components of the interventions are sufficient to improve health and promote healthy behaviors.

1.10 The Current Studies

The current study extends prior research testing links between positive affect and patterns of stress physiology that may be relevant to physical health and disease risk. Previous work elicited short-term increases in positive affect within the context of a laboratory stressor, while the animal literature demonstrates that chronic pleasurable experiences minimize stressor-evoked physiology. To date, no studies have tested whether increasing global positive affect, as compared to priming positive affect for a short period close in time to a stressor, may impact stressor-evoked physiology in humans. Although priming studies have been useful for elucidating a stress-buffering mechanism for positive affect, it remains unclear how these findings might generalize to naturalistic conditions. One extension of these findings is to teach skills that can be used to evoke or sustain positive affect as a means of protecting against psychological stressors and concurrent physiological responses to those stressors. Thus, the current study aims to implement a positive psychological intervention in young adults to test whether enhancing positive affect accelerates cardiovascular recovery (heart rate and blood pressure) to psychological stress. Prior to testing the overall study hypotheses, two pilot studies were conducted to validate (1) a positive psychological intervention and (2) an online social-evaluate stress task.

2.0 Pilot Study 1: Validating a Positive Psychological Intervention

In the first pilot study, participants were randomized into a positive psychological intervention or active control condition. Both conditions completed online activities every other day for two weeks. Participants completed the activities every other day, based on previous findings that completing positive psychological activities less frequently may paradoxically lead to greater enhancement in positive affect, potentially due to habituation from performing activities daily (Sin & Lyubomirsky, 2009). Positive psychological interventions of this duration (two weeks) have been shown to effectively increase positive affect (d = 0.35; Boiler et al., 2013; Lyubomirsky et al., 2009), while presumably increasing participant adherence (Beatty & Binnion, 2016).

2.1 Study Aims

Aim 1. To test whether a positive psychological intervention enhances positive affect.

Prediction: Individuals receiving the positive psychological intervention will demonstrate greater gains in positive affect from pre- to post-intervention relative to those in the control condition.

Sensitivity Analysis. Which subset(s) of positive affect (*i.e.*, low vs high arousal) are influenced by a positive psychological intervention?

Prediction: Individuals receiving the positive psychological intervention will exhibit greater gains in high-arousal positive affect from pre- to post-intervention relative to those in the control condition. The intervention will selectively target high-arousal positive affect due to the high-arousal nature of the chosen activities and emotions they are likely to evoke.

Ancillary Aim 1. To test whether a positive psychological intervention alters other facets of well-being (*e.g.*, optimism, eudaimonic well-being, life satisfaction).

Prediction: Individuals receiving the positive psychological intervention will exhibit greater gains in eudaimonic well-being, life satisfaction, and optimism from pre- to post-intervention relative to those in the control condition.

Ancillary Aim 2. To test whether a positive psychological intervention alters perceived social support, perceived loneliness, negative affect, depressive symptoms, anxiety symptoms, or perceived stress.

Prediction: Individuals receiving the positive psychological intervention will have greater decreases in negative affect and perceived stress, depressive symptoms, anxiety symptoms, and loneliness relative to those in the control condition. Individuals receiving the positive psychological intervention will exhibit greater increases in perceived social support relative to those in the control condition.

2.2 Methods

2.2.1 Participants

Participants (N = 250) ages 18 – 45 were recruited from the University of Pittsburgh undergraduate subject pool. Participants were deemed ineligible if they were under the age of 18; currently prescribed medications for cardiac arrhythmias; reported a history of heart surgery, myocardial infarction, or stroke; or currently have symptoms consistent with COVID-19.

2.2.2 General Procedures

To minimize in-person contact between participants and staff amidst the growing concern related to COVID-19, all study procedures were administered online. Those interested in the study completed an online screening survey. If eligible, participants were randomized to either an active control condition or a positive psychological intervention, stratified by sex, year in college, and trait positive affect. Participants received a survey link containing the consent form and a video explaining the study procedures. After electronically signing the consent form, participants then completed two sets of baseline questionnaires online. In both conditions, participants then completed one writing activity every other day for two consecutive weeks. All participants received two text message reminders – one in the morning and a second in the evening – on the days when they were scheduled to complete a writing activity. Each writing activity took no longer than ten minutes to complete. At the end of the two weeks, participants had two final (post-intervention) sets of questionnaires that were completed online within 3 days of their last writing activity. All procedures were implemented in accordance with the University of Pittsburgh's Institutional Review Board.

2.2.3 Intervention Conditions

Active control condition. The purpose of the active control condition was to control for the potential effect of completing writing activities on positive affect. To control for the act of completing writing activities every other day, the active control condition documented their activities for that day. Notably, documenting daily activities may increase positive affect or other psychological factors of interest, especially when reflecting on or ascribing meaning to those activities. For example, writing about an emotional response to a stressful event can reduce rumination and depressive symptoms associated with that event (*e.g.*, Sloan et al., 2008). A recent meta-analysis suggests that this style of writing has little impact on positive psychological functioning (r = 0.03; Frattaroli, 2006); however, extra precautions were taken to minimize increases in positive affect in response to writing daily activities. Participants were therefore encouraged to process their daily activities superficially by receiving the following instructions: (1) list each activity in brief, incomplete sentences, (2) document only facts about performing the activities, and (3) to *not* provide any information about emotional responses to performing the activities. By following these instructions, participants are presumably deriving less meaning from their activities, which may minimize gains in positive affect in the active control condition (Pennebaker, 1993).

Positive psychological intervention. Participants in the positive psychological intervention group were also asked to complete a writing activity every other day, with each activity corresponding to a particular skill. The following six activities were selected for the intervention: (1) signature strengths, (2) three good things, (3) acts of kindness, (4) best future self, (5) writing and delivering a gratitude letter, and (6) savoring with mindful photography (see Appendix A for more details about each of the activities). The activities were selected to encompass a range of affective and cognitive strategies that can enhance positive emotions without focusing on any one specific emotion (*e.g.,* optimism or gratitude). By providing a list of six activities, participants were able to select the activities that were most helpful to them. Because there are individual differences in *what* makes people happy (*e.g.,* Sin, Della Porta, & Lyubomirsky, 2011), allowing participants to choose their activities may maximize the benefits of the intervention. Another benefit of providing a 'menu' of activities to use is to prevent habituation that can occur with repeating the same positive psychological activity multiple days (Lyubomirsky & Layous, 2013). Providing flexibility in the activities that participants can use may therefore reduce habituation and maximize gains in positive affect in response to the intervention.

Online prompt administration. All participants, regardless of condition, received two text message notifications daily. In the control condition, the first text message was simply a reminder that they would complete a writing activity later that day. The second text message included a survey link so that they could list their daily activities. In the intervention condition, the first text message included a survey link asking which positive psychological activity they wanted to complete that day. The second text message provided the survey link for that writing activity. After completing their respective activities, participants were then asked to answer some brief questions assessing mood, health behaviors, and social functioning for that day (see 'Questionnaires' section and Appendix A.2 Positive Psychological Intervention for more details).

Intervention check. All participant responses to the writing prompt were analyzed using the Linguistic Inquiry and Word Count software (LIWC; Pennebaker, Francis, & Booth, 2001).

This software uses a dictionary to classify words by specific categories (*e.g.*, positive emotion words, social words, time orientation, etc) and calculates the percentage of words in each category by the total number of written words. The LIWC software was used to calculate the percentage of positive emotion words written for each activity to estimate the efficacy of the positive psychological intervention to increase positive affect relative to the control condition.

2.2.4 Questionnaires

At baseline, participants were asked to report their demographic information including age, sex, race, parental education (Gianaros, et al., 2008), perceived socioeconomic standing (Adler et al., 2000; Goodman et al., 2007), and use of psychotropic medications. Participants also completed a series of questionnaires at baseline and post-intervention measuring the following variables: trait positive and negative affect (Positive and Negative Affective Schedule (PANAS; Watson, Clark, & Tellegen, 1988) and Positive and Negative Emotional Style; Cohen et al., 2003; in general and last few days), anxiety and depressive symptoms (PROMIS-Anxiety and PROMIS-Depression; Pilkonis et al., 2011), perceived stress (Perceived Stress Scale; Cohen, Kamarck, & Mermelstein, 1994), psychological wellbeing (Psychological Wellbeing Scale; Ryff, 1989), optimism (Life Orientation Test-Revised; Scheier, Carver & Bridges, 1994), life satisfaction (PROMIS- General Life Satisfaction; Salsman et al., 2014), loneliness (UCLA Loneliness Scale; Russell, Peplau, & Ferguson, 1978), social support (Interpersonal Support Evaluation List; Cohen et al., 1985), sleep (quality and duration), and physical activity (duration for light and moderate-to-vigorous activity). To minimize participant burden and survey fatigue, participants completed two sets of baseline and post-intervention questionnaires so that each set of questionnaires took no more than 15 minutes to complete. Additional questions were also administered after each writing activity. Post-activity questions included the 18-item positive and negative emotional style and one-item questions assessing loneliness, social connectedness, perceived stress, academic stress, light and moderate-to-vigorous physical activity, sleep duration, and sleep quality. Please refer to Table 1 for the complete list of questionnaires and their administration schedule. Detailed information for each questionnaire can also be found in Appendix B.1 Baseline Questionnaires).

2.2.5 Statistical Analyses

Baseline comparisons. To check whether participants were successfully randomized into conditions, a *t*-test or chi-square was used to compare baseline characteristics between the two groups. Any group differences at baseline were used as covariates for all subsequent analyses to control for any inherent group differences that may affect the interpretation of the results.

General Statistical Methods. To reduce the number of statistical tests, Pearson's correlations were first calculated within a variable set and variables that were strongly correlated ($|r| \geq 0.50$) were included in the same model as dependent variables. Then, a semi-parametric 2-way repeated measures MANOVA was used to assess changes in a set of variables from pre-to post-intervention using the r package MANOVA.RM (Friedrich, Konietschke, & Pauly, 2018). The benefit of this semi-parametric approach is that it does not assume multivariate normality or homogeneity of variance-covariance matrices. Analyses were interpreted based on the parametric bootstrap modified ANOVA-type statistic (denoted by Q_N) and any main effects or interactions that were statistically significant at the conventional threshold of $p < 0.05$, were further assessed by bivariate post-hoc comparisons with Bonferroni adjustment.

Aim 1. To test whether a positive psychological intervention enhances positive affect, all four measures of positive affect (PANAS-PA-general, PANAS-PA-few days, PES-general, PES-few days) were considered as a set of dependent variables.

Sensitivity Analysis. To determine which subset(s) of positive affect (*i.e.,* low vs high arousal) are influenced by a positive psychological intervention, all three subsets of positive affect from the positive emotional style questionnaire were considered as a set of dependent variables (calm, well-being, and vigor).

Ancillary Aim 1. To test whether a positive psychological intervention alters other facets of well-being, optimism, eudaimonic well-being, and life satisfaction were considered as a set of dependent variables.

Ancillary Aim 2. To test whether a positive psychological intervention alters perceived social support or perceived loneliness, both outcomes were considered as one set of dependent variables. To test whether a positive psychological intervention alters negative affect, depressive symptoms, anxiety symptoms, and perceived stress, and all four measures of negative affect (PANAS-NA-general, PANAS-NA-few days, NES-general, NES-few days) were considered as one set of dependent variables.

Exploratory Analyses. Exploratory aims, analytic plans, and results can be found in Appendix C.1 Exploratory Aims, Appendix C.2 Exploratory Analyses, and Appendix C.3 Exploratory Results.

2.3 Results

2.3.1 Participant Characteristics

Participants completed a survey prior to obtaining informed consent to determine eligibility. Of the participants screened (N = 262), some did not meet the inclusion criteria (N = 2), while others withdrew from the study prior to obtaining informed consent (N =10). Therefore, a total of 250 participants (Control n = 129; Intervention n = 121) were enrolled in the study. Participants were excluded from analyses if they completed fewer than six of the eight writing prompts (N =16); failed to complete the post-intervention questionnaires (N = 6); or failed attention checks that were included in the questionnaires (N = 3); leading to a final sample of 225 participants (Control n = 122; Intervention n = 103; see Figure 2 for study flow chart).

The overall sample had a mean age of 18.7 ± 2.1 years and was 76.9% female. The majority of participants identified as Caucasian (64.4%) and were in their freshman year of college (68.4%; see Table 2). There were no statistically significant differences in age ($t(127) = -0.58$, $p = .56$), sex ($\chi^2(1, N = 225) = 0.53, p = .46$), race ($\chi^2(4, N = 225) = 5.58, p = .23$), or year in college ($\chi^2(4, N = 225) = 2.02, p = .73$) between the control and intervention conditions. As such, no covariates were used in subsequent analyses. Similarly, both conditions reported similar levels of trait positive affect before randomization (PANAS-PA: $t(216.47) = 0.21$, $p = 0.83$; PES: $t(217.24) = -1.28$, $p = .20$), suggesting that the stratified randomization was successful. Participants in the intervention condition used a greater percentage of positive emotion words during their writing activities ($M = 6.89$, $SD = 1.61$) relative to the control condition ($M = 1.05$, $SD = 1.14$; $t(179.59) = -30.66$, $p < .001$), suggesting that the intervention successfully elicited more positive emotions during the positive psychological activities relative to the control activity.

2.3.2 Aim 1: Positive Affect

Because all indicators of positive affect were correlated at $r \geq 0.50$ (range $r = 0.61 - 0.79$; Table 3), they were simultaneously entered in a single MANOVA as simultaneous outcome variables. There was a significant main effect of time ($Q_N = 46.1$, $p < 0.001$), such that positive affect decreased from baseline to post-intervention across both conditions. Furthermore, post-hoc analyses indicate that these effects are primarily due to changes reports of general positive affect (PANAS-PA: $t(431.2) = -5.60$, $p < .001$; PES: $t(441.9) = -3.22$, $p = .001$) and PANAS-measured positive affect in the past few days ($t(447.7) = -2.41$, $p = .02$). There was no main effect of condition ($Q_N = 8.89$, $p = .11$) or condition x time interaction ($Q_N = 12.36$, $p = .49$) on positive affect (Figure 3).

Sensitivity Analysis. Well-being and vigor were correlated at $r = .59 - .80$, while calm was correlated with vigor at $r = .17 - .37$ and well-being at $r = .33 - .48$. Therefore, well-being and vigor were entered into one model while calm was assessed with a repeated-measures ANOVA. Well-being and vigor decreased across time ($Q_N = 18.1$, $p = .01$), but there was no main effect of condition ($Q_N = 10.1$, $p = .10$), or condition x time interaction ($Q_N = 1.5$, $p = .61$). By contrast, self-reported calm was lower in the control condition relative to the intervention condition ($Q_N = 7.1$, $p = .049$), but did not differ as a function of time ($Q_N = 4.1$, $p = .12$) or condition x time interaction ($Q_N = 0.9$, $p = .56$).

2.3.3 Ancillary Aim 1: Other Facets of Well-being

Optimism, eudaimonic well-being, and life satisfaction were all correlated at $r > 0.50$ (range $r = 0.58 - 0.63$; Table 3) and were entered into the model simultaneously. There was no main effect of condition ($Q_N = 0.98$, $p = .75$), no main effect of time ($Q_N = 2.41$, $p = .43$), and no condition x time interaction ($Q_N = 1.14$, $p = .70$) on other facets of well-being (Figure 4).

2.3.4 Ancillary Aim 2: Social Factors and Negative Affect

Perceived social support and perceived loneliness were correlated at $r = -0.70$ (Table 3) and were included as simultaneous dependent variables. There was no main effect of condition ($Q_N = 4.71$, $p = .11$), no main effect of time ($Q_N = 0.90$, $p = .96$), and no condition x time interaction ($Q_N = 0.63$, $p = .62$) on social factors (Figure 5).

Negative affect, anxiety, depressive symptoms, and perceived stress correlated at $r > 0.50$ (range $r = 0.53 - 0.84$; Table 3) and were included in the same models as dependent variables. There was a main effect of time ($Q_N = 32.10$, $p = .02$), such that negative affect decreased from baseline to post-intervention in both conditions. Furthermore, post-hoc analyses indicate that these effects are primarily due to changes reports of general negative affect (PANAS-NA: $t(445.95) = -4.86$, $p < .001$; NES: $t(447.88) = -2.14$, $p = .03$). There was no main effect of condition ($Q_N = 3.06$, $p = .69$) or condition x time interaction ($Q_N = 6.65$, $p = .35$) on aggregate indices of negative affect (Figure 6).

2.4 Discussion

Although participants randomized to the positive psychological intervention wrote more positive emotion words during their writing activities than the control condition, they did not show increases in self-reported positive affect in response to the intervention. The study findings are in contrast to prior work demonstrating that two-week positive psychological interventions can increase positive affect (Boiler et al., 2013; Lyubomirsky et al., 2009; White, Uttl, & Holder, 2019). The current positive psychological intervention also failed to influence indicators of eudaimonic well-being, life satisfaction, optimism, loneliness, perceived social support, or negative affect. Although this finding is in contrast with the study hypotheses, it is in line with more recent studies demonstrating that positive psychological interventions have smaller effects on psychological well-being and depressive symptoms than was previously reported (White, Uttl, & Holder, 2019).

The current study might have failed to increase positive affect for a few reasons. First, the participants could have been less engaged in the activities relative to previous studies. Due to the coronavirus pandemic, the positive psychological intervention was administered completely online through a survey link that was delivered by text message. It is therefore plausible that delivering the intervention by text message might have impacted the ability for participants to engage in the material relative to other means of administration (*i.e.,* writing it down in a diary, verbal discussion, etc). For example, taking handwritten notes is associated with a deeper understanding of concepts taught in class (Horbury & Edmonds, 2021; Mueller & Oppenheimer, 2014; but also see Morehead et al., 2019) and can enhance the ability to recall a list of words (Horbury & Edmonds, 2021; Mangen et al., 2015), relative to typewritten notes. This might suggest that writing the prompts down in a diary could have increased the level of engagement during a task, relative to typing the responses on a cell phone. Two studies to date have investigated the influence of writing modality on emotional writing tasks (*e.g.,* Pennebaker writing paradigm; Pennebaker, 1997); however, the evidence is mixed as to the relationship between writing modality and the therapeutic benefit of the task. One study demonstrated that an emotional writing task elicited greater emotional responses, led to greater self-disclosure, and was self-reported as more beneficial when written by hand rather than typed (Brewin & Lennard, 1999). A second study suggested that there was no difference in self-reported affect or written content, such as percentage of positive emotion words, when comparing a handwritten or typed response to an emotional writing task (Sharp & Hargrove, 2004). As such, it still remains unclear as to how completing a positive psychological intervention through text messaging could have impacted the study outcomes.

A second explanation as to why the current positive psychological intervention was not associated with increases in positive affect could be due to the variety of activities that were offered. While each of these activities, individually, has been demonstrated to increase positive affect (see Table 4), most short-term interventions (< 4 weeks) use a single skill for participants to work on rather than providing multiple positive psychological activities (Sin & Lyubomirsky, 2009; but also see Fordyce, 1977). The rationale for including multiple activities was to account for individual differences in what makes people happy (Sin, Della Porta, & Lyubomirsky, 2011) and preventing habituation that could occur when activities are repeated (Lyubomirsky & Layous, 2013). However, it is possible that two weeks is not enough time for participants to identify which activities were most beneficial to them *and* to develop the skills promoted by each activity. Along these lines, results from our exploratory analyses suggested that writing and delivering a gratitude letter was most strongly associated with gains in positive affect but, it was also the activity that was chosen less frequently with only 54% of the participants choosing to write a gratitude letter. This might suggest that the study participants were unable to learn which activities were most effective at eliciting positive affect within the two-week intervention. As such, longer interventions might be necessary for studies that provide a variety of positive psychological activities (*e.g.*, Celano et al., 2018a; Celano et al., 2018b).

Finally, it is important to consider the unique challenges of administering an online psychological intervention during a global pandemic. Data collection for this study occurred between September and November of 2020. For a broader context, data collection occurred prior to the development of COVID-19 vaccines when the national death toll was over 50,000 by the end of November (CDC, 2020, Provisional Death Counts for Coronavirus Disease 2019 Section). Locally, the Allegheny County infection rate climbed from ~ 400 cases per week in September to ~ 3,500 cases per week in November (Allegheny County Health Department, 2020, COVID-19 Weekly Data and Trends Section). At the University of Pittsburgh, all classes were online and those who lived on campus were restricted to interacting with a 'pod' of 3-5 other students based on the university housing assignments. With this in mind, it is perhaps unsurprising that college students have been a particularly vulnerable group during the pandemic and have reported more anxiety and stress during the pandemic relative to adults (Huang & Zhao, 2020; Wang et al., 2020). Furthermore, students *without* a pre-existing mental health condition were more likely to be negatively impacted by the pandemic compared to students with a history of mental health concerns (Hamza et al., 2020). Of interest, social factors have been strongly correlated with mental health during the pandemic, such that social isolation (d = 0.73; Hamza et al., 2020), lower perceived social support, and less social connection (d = 0.41 - 0.58; Graupensperger et al., 2020) are all associated with poorer mental health outcomes during quarantine. Because social support has been strongly linked to poor mental health during the pandemic, failing to address social factors in the current intervention could have negatively impacted the intervention. As such, positive psychological interventions administered during the pandemic may be more successful if they include activities aimed at increasing social factors (*e.g.*, loving-kindness meditation; active constructive responding; Hutcherson, Seppala, & Gross, 2008; Seligman et al., 2005), or facilitate social interactions by delivering the intervention in a group format (Sin & Lyubomirsky, 2009). Taken together, more work is necessary to understand how the pandemic might influence the efficacy of previously validated interventions and how facilitating social interactions might enhance intervention efficacy under the current circumstances.

As noted earlier, the two-week online positive psychological intervention did not influence psychological well-being, other indicators of well-being, or negative affect and related symptomatology. Two well-cited meta-analyses originally estimated that positive psychological interventions have moderate effects on psychological well-being (r = .10 - .29) and depressive symptoms (r = .11 - .31; Boiler et al., 2013; Lyubomirsky et al., 2009). However, a more recent study re-analyzed data from both meta-analyses to account for small sample sizes that are common within the aggregated studies. After weighting the study effects based on their sample size, which is common practice for meta-analyses, the ability for positive psychological interventions to enhance psychological wellbeing (r = .02 - .08) or reduce depressive symptoms (r = .02 - .08) was smaller than originally estimated (White, Uttl, & Holder, 2019). One common critique of studies that implement positive psychological interventions are the relatively small samples collected for each study. However, the current study collected data from 225 participants, a sample larger than previous studies, and also failed to demonstrate that a positive psychological intervention improves other facets of well-being or negative affect. Taken together, more work is necessary to understand the specific emotional and cognitive changes that can occur following various positive psychological activities and interventions.

In summary, the pilot study demonstrated that an online two-week positive psychological intervention did not enhance positive affect or other positive psychological factors during a global pandemic. It is likely that multiple factors, such as delivering the intervention online over a relatively short time period, offering too many activities, or failing to address social factors within the intervention all could have influenced the study outcomes. As already noted in the field (see Sin, Della Porta, & Lyubomirsky, 2011), more research is necessary to understand how to deliver positive psychological interventions in way that maximizes gains in positive affect.

3.0 Pilot Study 2: Validating a remote Trier Social Stress Test

Due to the coronavirus pandemic, research requiring in-person and psychophysiological assessments now confer a heightened level of infectious and disease risk to both participants and experimenters. Psychophysiological research involving cardiovascular and other organ system functioning during acute stress protocols have become especially risky because of the necessity for close and prolonged physical contact between experimenters and participants. However, acute stress protocols may be adapted for remote virtual data collection. One such protocol amenable to online adaptation is the Trier Social Stress Test (TSST; Kirschbaum, Pirke, & Hellhammer, 1993; Kudielka, Hellhammer, & Kirschbaum, 2007). During the TSST, participants complete speech and mental arithmetic tasks in front of a small evaluative audience. Although the laboratory version of the TSST is known to evoke robust emotional and physiological reactions (Kudielka, Hellhammer, & Kirschbaum, 2007), this version requires a minimum of three staff members (two evaluative interviewers as an audience, and one experimenter to administer task instructions, etc.). As a result, this resource intensive laboratory version of the TSST carries notable potential coronavirus infection risks to both participants and researchers. Furthermore, validating a fully remote administration of a virtual TSST may allow for populations that may not have been able to attend laboratory sessions previously (*e.g.,* limited transportation) to engage in stress research, even after the era of COVID-19. For these reasons, the first study aims to validate a completely remote version of the Trier Social Stress Test (rTSST).

Eligible participants were randomized into either a stress or control condition. All participants received a blood pressure monitor before their scheduled remote visit. During the remote visit, participants completed a series of tasks (delivering a speech and mental arithmetic) while taking blood pressure and heart rate readings throughout. Participants in the stress condition were invited to complete a second, slightly modified, remote stress task administered approximately one week after their first visit to assess test-retest reliability of the protocol. After their final task, all participants were debriefed, and stress participants were asked to provide feedback on their experience with the remote task.

3.1 Study Aims

Aim 1: To test the feasibility of a remote Trier Social Stress Test to induce emotional and cardiovascular responses relative to a control condition.

Predictions: The remote Trier Social Stress Test will be feasible with few reported issues during task administration. In addition, participant feedback will be incorporated to improve the administration of the remote Trier Social Stress Test.

Aim 2: To test the validity of a remote Trier Social Stress Test to induce emotional and cardiovascular responses.

Predictions: The remote Trier Social Stress Test will increase blood pressure, heart rate, negative affect, self-reported arousal, and anxiety in the stress condition relative to the control condition. Individuals in the stress condition will exhibit lower positive affect during the remote Trier Social Stress Test relative to controls.

Aim 3: To test the reliability of a remote Trier Social Stress Test to induce emotional and cardiovascular responses.

Predictions: The remote Trier Social Stress Test will show good test-retest reliability when re-administered to the same participant ~ 1 week later. The test-retest reliability will be high (ICC

~ 0.60) for all indices: positive affect, negative affect, anxiety, arousal, task engagement, heart rate, and blood pressure.

Ancillary Aim 1: To explore and assess the stability of various measures of recovery.

Rationale: Past research has quantitatively demonstrated that measures of reactivity are fairly stable within an individual; however, this has not yet been done for recovery. Previous studies have qualitatively described conceptual differences between the various ways of calculating recovery (Linden et al., 1997), but no studies to the authors' knowledge have quantitatively assessed which measures of recovery are most stable. Therefore, we will compare the test-retest reliability across various methods of calculating recovery to determine which method might be most suited for future research.

Exploratory Analysis 1: To explore group differences in task engagement.

Rationale: Because motivated engagement is associated with physiological changes during various tasks (*e.g.,* Singer, 1974), we were interested in comparing the level of self-reported engagement during the control and stress tasks. Some of the items also served as a manipulation check, since it is expected that the stressful task required more effort to complete and would be more difficult than the control task.

3.2 Methods

3.2.1 Participants

Participants (*N* = 69) ages 18 – 45 were recruited from the University of Pittsburgh undergraduate subject pool. Participants were deemed ineligible if they were currently pregnant, taking medications for cardiac arrhythmias, or reported a history of heart surgery, myocardial infarction, or stroke. All participants had access to a stable internet connection on either a desktop computer or laptop.

3.2.2 General Procedures

Eligible participants received blood pressure monitors by contactless delivery before their scheduled remote study visit. An email with the Zoom meeting ID and password was sent to the participants to reduce the risk of 'zoom bombing'. Upon arrival, participants were first asked about their adherence to the pre-visit restrictions (Table 5). Participants who did not comply with pre-visit restrictions were asked to reschedule their visit. As with the in-person version of the TSST, there were three interviewers that the participants saw on their screen. In addition to the three interviewers, the Zoom session was also recorded. Participants were instructed on how to fit the blood pressure cuff and how to take measurements before beginning the study procedures. All participants then completed a ten-minute baseline period (while sitting still and remaining quiet), completed a speech and mental math task, and watched a series of videos during the recovery period. A subset of the participants randomized to the stress condition (N = 31) participated in a second virtual session, approximately one week apart. The task instructions during the second study visit were slightly modified. All procedures were implemented in accordance with the University of Pittsburgh's Institutional Review Board and all study procedures can be found on the study OSF page (https://osf.io/eg5dr/).

3.2.3 Virtual Trier Social Stress Test

Control condition. Participants in the control condition followed the same general procedures noted above (e.g., video chat by Zoom, instructions to set up blood pressure cuff, asked to minimize distractions). In the control condition, participants were on Zoom with a single researcher. Although the session was recorded, they were informed that this would not be used to review the participant's performance. Participants were told that they are in the control condition and that their involvement in the study was to see how speaking influences blood pressure. The speech task consisted of a conversation between the participant and researcher. During the conversation, the participant could talk about their hobbies, favorite TV show, movie, or book for five minutes. The researcher emphasized that the content of what was discussed is unimportant and that the research staff would help them maintain the conversation if they had a difficult time speaking for the full five minutes. Before the conversation, participants were given three minutes to write down any talking points. After the speech task, participants performed a mental arithmetic task that consisted of counting by 2s for five minutes. In the instructions, participants were told that they could perform this task at a leisurely pace and to "just keep going" if they made any mistakes. They could start over at any point if the numbers got too high, or if they lost track of which number they were on. At the end of the (easy) mental arithmetic task, participants watched a series of videos. Blood pressure and heart rate readings every 2 minutes throughout the entire procedure. The research staff were friendly and helpful during these visits and used non-verbal behaviors to affirm the participant (*e.g.,* smiling and head nodding) throughout the tasks.

Stress condition. Participants in the stress condition were told that they were interviewing for their dream job and were allotted three minutes to prepare a speech for their interview. They were also informed that their recording would be used to further evaluate their task performance and nonverbal behaviors. During the interview, participants were asked to introduce themselves to the observers and to provide a rationale as to why they would be an ideal candidate for their dream job. While participants were preparing for the speech, two additional researchers joined the zoom meeting to act as judges. After preparation, the participants had five minutes to deliver their speech to the judges. If they finished their speech before the time limit, participants were encouraged to continue and/or were asked follow-up questions by the judges. Following the speech task, participants performed serial subtraction by 13s, starting from 1022, for five minutes. They were encouraged to work as fast as possible, while still answering accurately. If the participant made any mistakes, they were asked to start the task over. If participants performed well, time limits were enforced. Following the serial subtraction task, participants had a sixteen-minute recovery period. During the recovery period, participants watched a series of neutral videos. Participants who complete the rTSST a second time prepared a speech and completed a mental arithmetic task, but the task instructions were slightly modified (*e.g.,* different serial subtraction problem) to prevent the participant from practicing before the second session (Schommer, Hellhammer, & Kirschbaum, 2003). Participants were debriefed on the purpose of the study after they complete their final rTSST task.

Task questionnaires. Measures of positive affect, negative affect, and arousal (calm and anxiety) were collected throughout the virtual stress paradigm (see Figure 7) to assess emotional reactivity to the rTSST. All constructs were assessed by a single item (*e.g.*, “how positive do you feel?”) with responses being presented on a visual analogue scale. Task engagement was also assessed by five items that assessed task difficulty, motivation to perform well, effort exerted during the task, fatigue following the task, and how important it was to perform well on the task (see Table 6 for full list of emotional and motivational items). Demographic data were collected following the recovery videos, including race/ethnicity, year in college, program(s) of study, parental education, and perceived social standing for each parent and self. The specific items were identical to those asked in the first pilot study and can be found in **Appendix B.1 Baseline Questionnaires**.

3.2.4 Cardiovascular Measures

To receive the blood pressure monitor, participants were asked to meet research staff outside of the laboratory with both parties masked. After measuring the participant's arm circumference, the participants were provided with a bag that included the blood pressure monitor, an appropriately sized blood pressure cuff, extra batteries, and alcohol swabs so that the participants could clean study equipment before bringing it into their home. Blood pressure and heart rate were monitored by an Omron blood pressure monitor (Model: 7051T; Omron Healthcare, Inc; Kyoto, Japan). The Omron 7051T outperforms other commercial monitors in terms of accuracy (Hoffmann-Peterson et al., 2015), while also demonstrating adequate reliability across devices (*ICC* = 0.96; De La Figuera et al., 2013) and within subjects (~2mmHg *SD* within subject variability in adults; Mengden et al., 2010; *ICC* = 0.50 – 0.81 in adolescents; Christofaro et al., 2009). During the Zoom visits, blood pressure and heart rate were collected once every two minutes starting from the beginning of the first task until the end of the recovery period (Figure 7). Cardiovascular data were reduced by averaging across the following periods: baseline, speech task (preparation and delivery), mental arithmetic task, and recovery. The eight recovery values were reduced to four measures by averaging every two measurements.

3.2.5 Post-task Feedback

After the final test administration (for those completing two sessions), the following open-ended questions were asked to stress participants: (1) Did you believe that the interviewers were trained to monitor and assess your speech and behavior during the task? (2) How do you think doing these tasks online might compare to doing these tasks in-person? (3) Do you think that it was more difficult or stressful to do these tasks on zoom (compared to doing them in-person)? (4) How did you feel about having the session video recorded? (5) How easy or difficult was it for you to take your own blood pressure? and (6) Is there any additional feedback or comments that you have about the study?

3.2.6 Statistical Analyses

Feasibility. Feasibility was operationalized to include participant feedback about the remote Trier Social Stress Test as well as any researcher-documented issues that occurred during administration (*e.g.,* internet connection was unstable, participant was distracted by a family member part-way through the task, etc). Because these data are qualitative in nature, themes of participant feedback are described as well as any issues that occurred and ways to problem-solve these issues for future protocol administrations.

Validity. A semi-parametric two-way repeated measures MANOVA was used to assess (1) cardiovascular responses and (2) emotional responses to the rTSST between the stress and control conditions. The test statistic was calculated using a parametric bootstrap modified ANOVA-type statistic (Q_N) within the r package MANOVA.RM (Friedrich, Konietschke, & Pauly, 2018). The benefit of a semi-parametric approach is that it does not assume multivariate normality or homogeneity of variance-covariance matrices. The modified ANOVA-type statistic (Q_N) and *p*-values are estimated by parametric bootstrapping procedures, such that no degrees of freedom are reported for results calculated using a modified repeated measures MANOVA. Any findings that are statistically significant at the conventional threshold of $p < 0.05$ were tested by univariate post-hoc comparisons with Bonferroni correction. All cardiovascular variables that are correlated at $r \geq 0.50$ were included as a set of dependent variables within the same model. Similarly, all variables assessing emotional responses (negative affect, arousal, anxiety, and positive affect) that are correlated at $|r| \geq 0.50$ were also included as dependent variables within the same model. If the model is statistically significant at the conventional threshold of $p < 0.05$, then bivariate post-hoc comparisons were performed with Bonferroni adjustment (Friedrich, Konietschke, & Pauly, 2018).

Test-retest Reliability. A subset of participants in the stress condition completed a second rTSST approximately one week after their first visit. To assess test-retest reliability, reactivity was first calculated as a delta change score from baseline (task - baseline). Reactivity values were then calculated separately for the two tasks (speech and mental arithmetic). Recovery was calculated a few different ways including (a) delta change score from baseline, (b) delta change score from task, (c) percent change from baseline, (d) percent change from task, and (e) area under the curve. The test-retest reliability of reactivity and recovery was calculated by intraclass correlations (2-way mixed effects model with absolute agreement; Koo & Li, 2016).

Stability of Recovery. The various methods for calculating recovery were compared in two ways. First, the correlations were reported between the methods for calculating recovery. Second, the intraclass correlation (2-way mixed effects model with absolute agreement; Koo & Li,

2016) were calculated for all recovery methods in the subset of participants that performed a second remote Trier Social Stress Test.

Task Engagement. Differences in task engagement was first assessed as the average between all five items of task engagement. Group differences were assessed by a *t*-test since these items are only asked once (after the stress tasks). If there was a statistically significant difference between the two groups, then each individual item was also assessed for statistical significance to understand which individual item(s) most strongly differ between the two groups.

3.3 Results

3.3.1 Participant Characteristics

Individuals interested in participating received a phone call to assess eligibility and to review and electronically sign the consent form. Of the participants screened (N = 83), a few did not meet the inclusion criteria (N = 2), while others withdrew from the study prior to obtaining informed consent (N =2). Therefore, a total of 79 participants (Control n = 40; Intervention n = 39) were enrolled in the study and randomized to a condition. Some participants in each condition withdrew before their study visit either because they already had enough course credit (Control n = 2); had a scheduling conflict (Control n = 2; Intervention n = 1); were in isolation as a result of potential COVID exposure (Control n = 2; Intervention n = 1); or had cancelled their participation without providing a reason (Control n = 2). The final sample consisted of 69 participants (Control n = 32; Intervention n = 37). Of the 37 participants allocated to the stress condition, the majority of participants completed a second study visit (n = 31; see Figure 8 for study flow chart). Stress participants who did not participate in a second visit cited the following reasons: were not interested in a second session at baseline (*n* = 1); had enough credits (*n* = 3); declined to participate following their first visit (*n* =2); or were unable to attend because of COVID-related isolation (*n* = 2).

The overall sample had a mean age of 18.8 ± 3.3 years and was 73.9% female. The majority of participants identified as Caucasian (69.6%) and in their freshman year of college (47.8%; see Table 7). There were no statistically significant differences in age ($t(31.8) = 1.41$, $p = .17$), sex ($\chi^2(1, N = 69) < 0.01$, $p = .99$), race ($\chi^2(4, N = 69) = 4.28$, $p = .37$), year in college ($\chi^2(3, N = 44) = 2.99$, $p = .39$), or psychotropic medication use ($\chi^2(1, N = 69) = 0.03$, $p = .87$) between the control and stress conditions. Participants allocated to each condition did not differ in their levels of resting blood pressure (SBP: $t(63.7) = 1.69$, $p = 0.10$; DBP: $t(46.7) = 1.61$, $p = .11$) or heart rate ($t(57.4) = -0.68$, $p = .50$) at baseline. Similarly, there were no group differences in self-reported positive emotions ($t(64.24) = 0.19$, $p = .84$) negative emotions ($t(66.0) = -0.78$, $p = .44$), calmness ($t(65.75) = -0.44$, $p = .67$), or anxiety ($t(64.54) = -0.32$, $p = .75$) at baseline (see Table 7 for full baseline characteristics). Because there were no group differences in baseline variables, no covariates were included in subsequent analyses.

3.3.2 Aim 1: Feasibility

In reviewing the study documentation, only a small fraction of study participants encountered technical issues (*N* = 9; 10.1%) or were unable to setup their environment in a way that was consistent with other study participants (*N* = 21; 30.4%; see Table 8). The feedback survey was only administered to participants in the stress condition. Due to an administration error, 18 (48.6%) feedback surveys were missing from the current sample. Of the participants who did complete the feedback survey, a majority of participants believed that the judges were trained to monitor and assess their speech and behavior (N = 16; 84.2%); thought that the tasks would be worse in person (N = 9; 47.4%); more difficult or stressful in person (N = 10; 52.6%); did not mind the video session being recorded (N = 14; 73.7%); and found taking their own blood pressure to be easy (N = 16; 84.2%; full results reported in Table 8).

3.3.3 Aim 2: Validity

Calmness and negativity were correlated at $r < |0.50|$, such that two separate semi-parametric MANOVAs were conducted: calmness and positivity were entered together as dependent variables in one model and anxiety and negativity were entered together as dependent variables into a second model (see Table 9 for correlations between all baseline variables). There was a main effect of group on positivity and calmness ($Q_N = 41.3$, $p < .001$), such that control participants reported more positivity and calmness relative to stress participants. There was also a main effect of time ($Q_N = 122.3$, $p < .001$), indicating that overall, positivity and calmness were lowest during the task relative to baseline and recovery values. Finally, there was also a group x time interaction ($Q_N = 41.4$, $p < .001$). Post-hoc analyses suggested that stress participants reported less positivity and calmness during the task relative to control participants (see Table 10 for mean, standard deviations, and post-hoc comparisons of emotional variables by condition across all time points).

The model investigating anxiety and negativity revealed a main effect of group (Q_N = 65.8, $p < .001$), such that control participants reported less negativity and anxiety relative to stress participants. There was also a main effect of time ($Q_N = 95.0$, $p < .001$), suggesting that negativity and anxiety were highest during the task than at baseline or recovery. Finally, there was also a group x time interaction (Q_N = 32.1, p < .001). A post-hoc analysis indicating that stress participants reported more negativity and anxiety during the task relative to control participants. In addition, stress participants also continued to report greater negativity, but not anxiety, during the recovery period relative to controls (see Table 10 for post-hoc analyses and Figure 9 for graphs depicting changes in self-reported emotions across time by condition).

For physiological measures, one control participant had too many dropped readings during the task, such that reactivity scores could not be calculated for them. As such, the physiological data included a total of 68 participants including 31 control and 37 stress participants. Because heart rate and systolic blood pressure were only modestly correlated at baseline (r = .07), two separate models were used to evaluate how blood pressure and heart rate changed during the task by condition. In the first model, systolic and diastolic blood pressure were simultaneously entered into the model as dependent variables. One control participant was removed from the analyses because they were identified as an outlier (> 3SD from the mean), however removal of this participant did not alter the study results. There was a main effect of time (Q_N = 175.5, p < .001; Table 11), such that both systolic and diastolic blood pressure were higher during the tasks relative to baseline and recovery periods. There was no effect of group (Q_N = 4.4, p =.12), or group x time interaction (Q_N = 14.7, p = .28 Figure 10).

A repeated measures ANOVA was performed to assess an effect of group, time, and their interaction on heart rate. There was a main effect of time (F(1, 372) = 70.7, p < .001), such that heart rate was higher during the tasks relative to baseline and recovery periods. There was no main effect of group (F(1, 62) = 2.6, p = .12); however, there was a group x time interaction (F(6, 372) = 4.0, p < .001; Figure 10). Post-hoc analyses for the group x time interaction indicate that stress participants exhibited a faster heart rate during the mental arithmetic task relative to the control participants (Table 11).

3.3.4 Aim 3: Reliability

Change scores of emotional reactivity to the remote TSST demonstrated low reliability when participants were tested approximately one week later: positivity (ICC = 0.35, p =.02), calm (ICC = 0.37, p =.02), negativity (ICC = 0.12, p =.27), and anxious (ICC = 0.28, p =.048).

Of the 31 stress participants who completed a second study visit, 28 had complete physiological data from both study visits. When reliability was assessed separately for the speech and math tasks of the remote TSST, heart rate reactivity (Speech: ICC = 0.60, $p < .001$; Math: ICC = 0.57, $p < .001$) demonstrated good reliability one week later. However, systolic blood pressure reactivity (Speech: ICC = 0.11, $p < .29$; Math: ICC = 0.32, $p = .03$) and diastolic blood pressure reactivity (Speech: ICC = -0.11, $p = .70$; Math: ICC = 0.01, p =.48) demonstrated poor reliability when assessed one week later (see Table 12).

Because reliability was significantly lower for cardiovascular reactivity than anticipated, a set of exploratory analyses were conducted that were not pre-registered. First, reactivity was calculated using additional approaches including percent change from baseline, and area under the curve approaches. Of the methods used to calculate reactivity, area under the curve approaches demonstrated the highest reliability across all cardiovascular measures (all ICCs > 0.60, all *p*s < .001 Table 12). Second, prior research suggests that averaging across stress tasks can increase the reliability of cardiovascular reactivity (Manuck, 1994). Therefore, reliability was also assessed by averaging across the two tasks for each measure of reactivity. Averaging reactivity across the two tasks increased the reliability for heart rate reactivity (HR: ICC = 0.72, $p < .001$), but not blood pressure reactivity (SBP: ICC = 0.27, p =.08; DBP: ICC = -0.01, p =.52).

3.3.5 Ancillary Aim 1: Stability of Recovery Measurements

Six different methods of calculating physiological recovery were used to assess stability across study visits. Of the six methods, only three consistently demonstrated high correlations between the study visits for heart rate and blood pressure recovery: percent change with respect to baseline values (PC-B; SBP: r = .81; DBP: r = .76; HR: r = .80), area under the curve with respect to ground (AUCg; SBP: r = .87; DBP: r = .81; HR: r = .75), and area under the curve with respect to increase (AUCi; SBP: r = .86; DBP: r = .80; HR: r = .73). See Table 13 and Table 14 for correlations between all measures of recovery for blood pressure and heart rate, respectively. These three methods of calculating recovery were also highly correlated with one another (range r = .99 - .80).

In line with the correlational results, the same three measures of recovery demonstrated high intraclass correlations for all cardiovascular measures (see Table 12): percent change with respect to baseline values (PC-B; SBP: *ICC* = .79; DBP: *ICC* = .69; HR: *ICC* = .79), area under the curve with respect to ground (AUCg; SBP: *ICC* = .87; DBP: *ICC* = .80; HR: *ICC* = .74), and area under the curve with respect to increase (AUCi; SBP: *ICC* = .85; DBP: *ICC* = .78; HR: *ICC* = .71).

3.3.6 Exploratory 1: Task Engagement

Average task effort differed by group (t(65.8) = -4.04, p < .001), such that individuals in the stress condition reported greater task effort relative to those in the control condition (Figure 11). When looking at each item of task engagement separately, participants in the stress condition reported greater effort (t(59.6) = -4.42, p < .001), task difficulty (t(64.8) = -10.7, p < .001), and fatigue (t(65.0) = -2.96, p = .004) relative to controls. There were no group differences in self-reported motivation (t(58.3) = 1.42, p =.16) or importance to perform well on the task (t(65.5) = -.34, p =.73). See Table 15 for group means and standard deviations for all measures of task engagement.

3.4 Discussion

The aim of the current study was to test the feasibility, validity, and reliability of a remote Trier Social Stress Test (rTSST). Overall, both the research staff and study participants indicated that it was feasible to deliver a stress test remotely. Although the rTSST induced emotional reactivity, participants in the stress condition did not exhibit greater cardiovascular reactivity relative to control participants. Finally, the reliability of the rTSST to induce emotional and cardiovascular reactivity was lower than anticipated and appeared to depend on the method used to calculate reactivity. The reliability of cardiovascular recovery following the rTSST demonstrated a similar pattern of results, such that area under the curve and percent change from baseline approaches were more reliable than other methods of calculating recovery.

Unfortunately, the current implementation of the rTSST did not induce cardiovascular reactivity relative to the control condition. There are a few plausible explanations as to why there were no observable group differences in cardiovascular reactivity: (1) the control condition was more stressful than anticipated, (2) the stress condition was less stressful than in-person administrations, and (3) the influence of speaking on blood pressure masked group differences in cardiovascular stress reactivity. First, although the control participants did not self-report that they reacted negatively to the task, it is possible that the nature of the control condition was still stressful. For example, some control participants deviated from the list of suggested topics to discuss during the speech task and instead discussed stressful events, such as their experiences with COVID-19. Discussing such emotionally valanced topics could have reasonably increased cardiovascular reactivity in the control group. Therefore, future implementations of a remote TSST should aim to control for the emotional valance during the speech task.

A second explanation could be that the stress condition was appraised as less stressful relative to classical (in-person) administrations of the TSST. During the in-person TSST protocols, the lead experimenter brings the participant into a novel room with the judges to perform their speech and mental arithmetic tasks. At the time of data collection, there was a single published study that demonstrated a rTSST could evoke cortisol and alpha-amylase activity in adolescents (Gunnar et al., 2021). Importantly, their rTSST protocol mimicked this process by moving the participant into a breakout room with the judges, rather than bringing the judges into the main Zoom room with the lead experimenter. There are two potential reasons why this step may be important to imitate during a remote version of the TSST. First, leading participants into a new room (or breakout room for the rTSST) may induce a sense of novelty that could reasonably increase perceptions of stress. Second, the participant may have positive or neutral interactions with the lead experimenter. As such, having the lead experimenter present during that task may serve as a source of social support that could reduce perceptions of stress during the task (*e.g.*, Thorsteinsson & James, 1999). For these reasons, it may therefore be important that the lead experimenter remains in the main Zoom room while the participant enters a separate break out room with the two evaluative rTSST judges.

A final reason as to why there were no group differences in cardiovascular reactivity could be due to the influence of speaking on the blood pressure. Cardiovascular reactivity was measured by aggregated cardiovascular data across the speech preparation and speech delivery periods. However, speaking itself increases both blood pressure and heart rate (Tardy, Thompson, & Allen, 1989; Zheng, Giovannini, & Murray, 2012; Lynch et al., 1981), with potentially larger effects on blood pressure relative to heart rate (Tardy, Thompson, & Allen, 1989). As such, it is possible that any group differences in cardiovascular responses to the stressful nature of the task could be masked by differences in the rate or rhythm of speaking. Therefore, future administrations should lengthen the duration of the speech preparation period. In doing so, the speech preparation and speech delivery periods could be compared across conditions to understand whether the act of speaking is masking any group differences in cardiovascular reactivity that occurs in response to the stressful nature of the task.

Based on previous research, it was anticipated that cardiovascular reactivity would be reliable (ICC > .60) when assessed one week later (*e.g.,* Manuck, 1994). Heart rate, but not blood pressure, reactivity demonstrated good test-retest reliability. One potential explanation for this finding is, as mentioned above, blood pressure may be more influenced by speaking relative to heart rate (increases of 20mmHg BP vs 11bpm HR; Tardy, Thompson, & Allen, 1989). In other words, factors relating to the rate and rhythm of speech might have influenced the blood pressure readings to a greater extent than the stressful nature of the rTSST. In a set of exploratory *post-hoc* analyses, blood pressure reactivity was found to be more reliable across study visits when measured using the area under the curve approaches compared to the more commonly used change score method. Although area under the curve approaches require more frequent sampling, it might include more nuanced information about how cardiovascular measures may change throughout the task, rather than averaging across all task measures. For example, if habituation occurs during the stressor, this nuanced information might not be captured when averaging across all task measures but would be represented within the area under the curve calculations. Furthermore, area under the curve methods also contain information about the rate of change (*i.e.,* slope) from baseline to task measures, which would be missing from change score calculations.

The benefits of using area under the curve approaches also extend to calculations of cardiovascular recovery. Similar to our reactivity findings, recovery was also most reliably measured using area under the curve approaches with all cardiovascular measures demonstrating good test-retest reliability (all ICCs > .72). In addition to area under the curve, percent change from baseline was another method of calculating recovery that demonstrated good test-retest reliability for all cardiovascular measures (all ICCs > .69). One benefit of calculating recovery by the percent change from baseline is that it may control for individual differences in reactivity (Linden et al., 1995). Although previous research has compared change score and residualizing approaches to calculating physiological reactivity (Llabre et al., 1991), no study has statistically compared area under the curve approaches to change scores, or percent change, leaving open the question as to which method of calculating physiological reactivity and recovery might provide more stable estimates.

There were minimal technical issues that were recorded by the staff during the test administration. Of the issues documented, some were attributed to using outdated versions of Zoom (*e.g.*, unable to record or unable to hide self-view). As such, it would be useful to include an extra Zoom visit before the rTSST to review the Zoom features and ensure the participant has the correct version of Zoom installed on their computer. This would also allow for more time to problem-solve any computer or internet-related issues before the participant completes their study visit. The other technical issues that arose during the rTSST included issues with fitting the blood pressure cuff appropriately. In some cases, the participants exhibited dropped blood pressure readings during the baseline period that could have indicated that the cuff was fitted inappropriately. As such, adding practice blood pressure readings to the protocol prior to collecting baseline measures might improve the quality of cardiovascular data.

Taken together, the results of the two pilot studies preclude a third study testing whether a positive psychological intervention can facilitate cardiovascular recovery following a psychological stressor. Instead, the third and final study implements several changes to the second pilot study with the aim of validating a rTSST to evoke cardiovascular reactivity. Furthermore, the various methods of calculating reactivity and recovery will be compared in attempts to replicate our findings indicating that area under the curve approaches are the most reliable methods for calculating reactivity and recovery in an independent sample.

4.0 Study 3: Improving on and Validating a Remote Trier Social Stress Test

The purpose of the current project is to build upon the second pilot study aimed at validating a remote version of the Trier Social Stress Test (rTSST) relative to a control condition. Results from the previous study suggest that a rTSST successfully induced emotional reactivity in the stress condition; however, cardiovascular reactivity was elicited in both the stress and control conditions. As such, methods from the pilot study were modified to (1) minimize the perceptions of social evaluation in the control condition; (2) reduce the likelihood of eliciting emotional responses during the control condition's speech task; (3) increase perceptions of social evaluation in the stress condition; (4) evoke a sense of novelty during the stress condition, despite the participants remaining in their home environment; and (5) try and reduce potential sources of measurement error in cardiovascular reactivity. A thorough list of the modifications to the study methods and rationale for each modification can be found in Appendix D.

4.1 Study Aims

Aim 1: To test the feasibility to administer a remote Trier Social Stress Test to induce emotional and cardiovascular responses relative to a control condition.

Predictions: The remote Trier Social Stress Test will be feasible with few reported issues during task administration. In addition, participants will provide feedback that we can integrate into improving the administration of the remote Trier Social Stress Test.

Aim 2: To test the validity of a remote Trier Social Stress Test to induce emotional and cardiovascular responses relative to the control condition.

Predictions: The remote Trier Social Stress Test will increase blood pressure, heart rate, and negative emotions in the stress condition relative to the control condition. Individuals in the stress condition will exhibit lower positive emotions during the remote Trier Social Stress Test relative to controls.

Ancillary Aim 1: To explore and assess the stability and reliability of various measures of cardiovascular reactivity to the remote Trier Social Stress Test.

Rationale: We previously predicted that the remote Trier Social Stress Test would show good test-retest reliability when re-administered to the same participant ~ 1 week later. However, our previous study suggested that the test-retest reliability of cardiovascular reactivity to the rTSST was low when reactivity was calculated using change scores and percent change methods (ICC = .003 - .57). Exploratory analyses suggested that cardiovascular reactivity calculated by area under the curve metrics were more reliable (ICC = .34 - .84). As such, we will compare the test-retest reliability across various methods of calculating reactivity to determine which method(s) are most reliable. We predict that the area under the curve metrics will continue to provide the most reliable estimates of cardiovascular reactivity.

Ancillary Aim 2: To explore and assess the stability and reliability of various measures of cardiovascular recovery following the remote Trier Social Stress Test.

Rationale: Past research has quantitatively demonstrated that measures of reactivity are fairly stable within an individual; however, this has not yet been done for recovery. Previous studies have qualitatively described conceptual differences between the various ways of calculating recovery (Linden et al., 1997), but no studies to the authors' knowledge have quantitatively assessed which measures of recovery are most stable. Our previous study suggested that, similar to measures of reactivity, cardiovascular recovery was most reliable when calculated by area under the curve and percent change from baseline metrics (ICCs = .69 - .87) relative to change scores or percent change from task calculations (ICCs = .05 - .59). We therefore aim to replicate this finding by comparing the test-retest reliability across various methods of calculating recovery to determine which method might be most suited for future research. We predict that the area under the curve and percent change from baseline metrics will continue to provide the most reliable estimates of cardiovascular recovery based on our previous study.

Exploratory analysis 1: To explore group differences in self-reported task engagement.

Exploratory analysis 2: Previous research suggests that those with higher trait positive affect may demonstrate faster blood pressure recovery following social-evaluative stressors relative to those with lower trait positive affect (DuPont et al., 2020). As such, we will investigate the relationship between trait positive affect and cardiovascular recovery following the rTSST.

Exploratory analysis 3: Previous research suggests that emotional reactivity and cardiovascular reactivity are only modestly correlated (r = 0.13 – 0.34); however, these studies focus on emotional reactivity of negative emotions without including any items assessing the emotional reactivity of positive emotions (*e.g.*, Feldman et al., 1999). As such, we will investigate the relationship between cardiovascular reactivity and positive/negative emotional reactivity to the rTSST.

4.2 Methods

4.2.1 Participants

Participants (N = 99) ages 18 – 47 were recruited from the University of Pittsburgh undergraduate subject pool. Consistent with the first rTSST study, participants were ineligible if they were under the age of 18; currently prescribed medications for cardiac arrhythmias; reported a history of heart surgery, myocardial infarction, or stroke; or currently have symptoms consistent with COVID-19.

4.2.2 Eligibility Zoom Visit

The protocol can be found on the study OSF page (https://osf.io/eg5dr/). The overall study procedures were nearly identical to the previous study, with the exception of the eligibility visit. This study implemented an extra Zoom visit to assess eligibility (rather than by phone) in an attempt to habituate the study participants to interacting with researchers over Zoom and to troubleshoot any Zoom-related technical issues prior to their study visit. Participants signed up for their eligibility visits online and automatically received a confirmation email with the Zoom link and password. Participants were then screened for eligibility, the consent form was reviewed, and interested participants were instructed on how to sign the consent form virtually. Participants were then randomized to a condition, scheduled for their study visit(s), and completed a few questionnaires (see 'Eligibility Visit Questionnaires' section below). Next, participants randomized to the stress condition were instructed on how to setup their screen in the same way that they would during their study visit (*e.g.*, viewing a stopwatch, Zoom in full screen, gallery view, hiding their own self-view). In doing so, research staff were allotted more time to help participants problem-solve any issues with Zoom, such as having an outdated version of the software, prior to their study visit. Stress participants were also informed ahead of time that they would complete their task in a breakout room with two other researchers.

Eligibility Visit Questionnaires. Participants completed questions about their demographic information and socioeconomic status as documented in the previous two pilot studies (see Appendix B.1 Baseline Questionnaires) and an additional question assessing English fluency (Is English your native language?). Trait positive and negative affect were also collected during the eligibility visit using the positive and negative emotional style questionnaire, asking participants how they felt 'in general.' Finally, all participants completed the Adult Reading Questionnaire, which assesses perceived reading and language ability, and reading concerns that are consistent with dyslexia (Snowling et al., 2012). The Adult Reading Questionnaire was included because control participants were asked to read from a script during the task, which could be perceived as a stressor, particularly in individuals who perceive themselves as having a low reading ability.

4.2.3 Virtual Trier Social Stress Test

Control condition. Participants in the control condition followed the same general procedures noted in the second pilot study (*e.g.,* video chat by Zoom, instructions to set up blood pressure cuff, asked to minimize distractions). In the control condition, participants were on Zoom with a single researcher and the visit was not recorded. Participants were told that their involvement in the study was to understand how speaking influences blood pressure. During the speech task, the participants were asked to read from a script that was written at a third grade reading level. The researcher emphasized that the participants were not being judged on anything related to the task and reassured that the purpose of the task was just to understand the relationship between blood pressure and speaking. Before reading the script aloud, participants were given five minutes to read through the script silently to themselves. After the speaking task, participants performed a mental arithmetic task that consisted of counting by 2s for five minutes. Participants were instructed to perform this task at a leisurely pace and that they could start over from two whenever the numbers got too high, or if they lost track of which number they were on. At the end of the (easy) mental arithmetic task, participants watched a final video. Blood pressure and heart rate readings were taken every 2 minutes throughout the entire procedure. The research staff were friendly and cooperative during these visits.

Stress condition. After the baseline blood pressure readings, participants in the stress condition were informed that they would be asked to deliver a speech in front of two judges. They were then asked to join a breakout room where two research assistants were waiting for them, named ‘Judge 1’ and ‘Judge 2’ on Zoom. Participants were then provided the instructions for their speech task – either a job interview (visit 1) or introducing themselves to a new class of twenty students (visit 2). They were also informed that their recording would be used to further evaluate their task performance and nonverbal behaviors. After five minutes of preparing for the speech, the visit was recorded, and participants were instructed that they had five minutes to deliver their speech to the judges. If they finished their speech before the time limit, participants were encouraged to continue and/or were asked follow-up questions by the judges. Following the speech task, participants performed serial subtraction by 13s, starting from 1022, for five minutes. They were encouraged to work as fast as possible, while still answering accurately. If the participant made any mistakes, they were asked to start the task over. If participants performed well, time limits were enforced. Following the serial subtraction task, participants were instructed to return to the main Zoom room. After returning to the main Zoom room, participants had a sixteen-minute recovery period where they watched a neutral video. Participants who complete the rTSST a second time prepared a speech and completed a mental arithmetic task, but the task instructions were slightly modified (*e.g.*, different serial subtraction problem) to prevent the participant from practicing before the second session (Schommer, Hellhammer, & Kirschbaum, 2003). Participants were debriefed on the purpose of the study after they complete their final rTSST task.

Task questionnaires. Measures of positive affect and negative affect were collected throughout the virtual stress paradigm (see Figure 7) to assess emotional reactivity to the rTSST. In contrast to the previous study, the positive and negative affect was assessed using adjectives from the positive and negative emotional style questionnaire. In doing so, positive and negative emotions were collected across the arousal continuum. All responses were presented on a visual analogue scale. Task engagement was also assessed by five items that assessed task difficulty, motivation to perform well, effort exerted during the task, fatigue following the task, and how important it was to perform well on the task.

4.2.4 Cardiovascular Measures

Participants had their arm circumference measured and received blood pressure monitor (Model: 7051T; Omron Healthcare, Inc; Kyoto, Japan) with an appropriately sized blood pressure cuff outside of the laboratory with both parties masked with facial coverings. During the Zoom visits, blood pressure and heart rate were collected once every two minutes starting from the beginning of the first task until the end of the recovery period (see Figure 7. Studies 2 & 3: Outline of laboratory visit, including psychological and physiological variables collected at each time point.). Cardiovascular data were reduced by averaging across the following periods: baseline, speech preparation/reading silently, speech delivery/reading aloud, mental arithmetic, and recovery. The eight recovery values were reduced to four measures by averaging every two measurements.

4.2.5 Post-task Feedback

During the initial study, post-task data were missing because of the way that the surveys were administered. In an attempt to reduce the amount of missing data, all study participants completed the same questions after each study visit. Participants who completed two study visits were asked the same questions after each study visit. The post-task feedback was modified from the form administered during the initial pilot study to have multiple choice responses based off of the themes from the first rTSST study's open-ended form. The complete list of feedback questions and multiple-choice responses is provided in Table 17.

4.2.6 Statistical Analyses

Covariates: Any group differences at baseline will be used as a covariate for all subsequent analyses to control for any inherent group differences that may affect the interpretation of the results. Demographic variables will be tested using a chi-square or t-test.

Aim 1: To test the feasibility to administer a remote Trier Social Stress Test to induce emotional and cardiovascular responses relative to a control condition.

Analysis: Feasibility is operationalized to include participant feedback about the remote Trier Social Stress Test as well as any researcher-documented issues that might occur during administration (*e.g.*, internet connection was unstable, participant was distracted by a family member part-way through the task, etc). Because these data are qualitative in nature, themes of participant feedback are described as well as any issues that occurred and ways to problem-solve these issues for future protocol administration.

Aim 2: To test the validity of a remote Trier Social Stress Test to induce emotional and cardiovascular responses relative to the control condition.

Analysis: A semi-parametric two-way repeated measures MANOVA was used to assess (1) cardiovascular responses and (2) emotional responses to the rTSST between the stress and control groups. Assuming that systolic blood pressure, diastolic blood pressure, and heart rate are all strongly correlated ($r \geq 0.50$), then they can all be included as dependent variables in the model. Similarly, all variables assessing emotional responses that are correlated at $|r| \geq 0.50$ were included as dependent variables in the same model. Repeated measures MANOVAs were calculated using a parametric bootstrap modified ANOVA-type statistic (Q_N) using the r package MANOVA.RM (Friedrich, Konietschke, & Pauly, 2018). This semi-parametric approach is beneficial because it no longer assumes multivariate normality or homogeneity of variance-covariance matrices. Because bootstrapping procedures were used to calculate the modified ANOVA-type statistic (Q_N) and estimate the p-values, no degrees of freedom are presented for results calculated using a repeated measures MANOVA. Any model estimates that are statistically significant at the conventional threshold of $p < 0.05$ were further examined using bivariate (t-test) post-hoc comparisons with Bonferroni correction.

Ancillary Aim 1: To explore and assess the stability and reliability of various measures of cardiovascular reactivity to the remote Trier Social Stress Test.

Analysis: A subset of the sample were asked to complete a second rTSST approximately one week after their first virtual session. Reactivity values were calculated separately for speech preparation, speech delivery, and mental arithmetic. Reactivity was calculated by the following methods: (a) delta change score from baseline, (b) percent change from baseline, (c) area under the curve with respect to ground, (d) area under the curve with respect to increase. The test-retest reliability of reactivity and recovery were calculated by intraclass correlations (2-way mixed effects model with absolute agreement; Koo & Li, 2016).

Ancillary Aim 2: To explore and assess the stability and reliability of various measures of cardiovascular recovery following the remote Trier Social Stress Test.

Analysis: The various methods for calculating recovery were compared two ways. First, we reported the correlations between the methods for calculating recovery. Second, the intraclass correlation (2-way mixed effects model with absolute agreement) was calculated for all recovery methods in the subset of participants that performed a second remote Trier Social Stress Test.

Exploratory analysis 1: Group differences in task engagement were assessed by a *t*-test since these items are only asked once (after the stress tasks). If there is a statistically significant difference between the two groups, then each individual item will also be assessed for statistical significance to understand which individual item(s) most strongly differ between the two groups.

Exploratory analysis 2: To investigate the relationship between trait positive affect and blood pressure recovery, we calculated the Pearson's correlation between trait positive affect and measures of cardiovascular recovery (as measured by the area under the curve with respect to increase) using only participants in the stress condition. If there is a statistically significant correlation between trait positive affect and a measure cardiovascular recovery, then each subcategory of positive affect (vigor, well-being, and calm) will be correlated with cardiovascular recovery to understand which subtype(s) of trait positive affect might be most strongly correlated with stress physiology.

Exploratory analysis 3: To investigate the relationship between cardiovascular reactivity and positive/negative emotional reactivity to the rTSST, we calculated the Pearson's correlation between emotional and cardiovascular reactivity. Both reactivity measurements will be calculated by the area under the curve with respect to increase method. Analyses will be conducted using data from stress participants during their first visit. Each emotional subcategory (vigor, well-being, calm, anxiety, depression, and hostility) was correlated with cardiovascular recovery to understand which subtype(s) of positive/negative emotional reactivity may be most strongly correlated with cardiovascular reactivity.

4.3 Results

4.3.1 Participant Characteristics

Interested students signed up for a screening visit on Zoom to assess eligibility, review the consent form, and receive instruction on how to use specific features on Zoom that are relevant for the study. One-hundred and five participants were screened, of which a few were no longer interested after reviewing the consent form (N = 4). Therefore, a total of 101 participants (Control n = 51; Stress n = 50) were enrolled in the study and randomized to a condition. Two participants (Control n = 1; Stress n = 1) withdrew from the study after signing the consent form but before participating in the study visit. As such, the final sample consisted of 99 participants (Control n = 50; Stress n = 49). Of the 49 participants allocated to the stress condition, nearly half completed a second study visit (n = 25; see Figure 12 for study flow chart). Participants in the stress condition without a second study visit were either uninterested in a second session at baseline (n = 13); were no longer interested after the first visit (n = 3); cited a scheduling conflict (n = 2); noted personal reasons (n = 2); were unable to attend because of COVID-related isolation (n = 2); appeared distressed during their first visit and were immediately debriefed, making them ineligible for a second study visit (n = 1); or did not provide a reason (n = 1).

The sample had an average age of 19.7 ± 3.5 years and was 54.5% female. Most participants identified as Caucasian (67.7%) and were in their freshman year (65.7%; see Table 16). Participants allocated to the control and stress conditions did not differ in age ($t(53.7) = -1.6$, $p = .12$), sex ($\chi^2(1, N = 99) < 0.01$, $p = .99$), race ($\chi^2(4, N = 99) = 3.05$, $p = .55$), year in college ($\chi^2(3, N = 99) = 4.05$, $p = .40$), or psychotropic medication use ($\chi^2(1, N = 99) < 0.01$, $p = .99$). There were also no significant group differences in their levels of resting blood pressure (SBP: $t(95.9) < -.01$, $p = 0.99$; DBP: $t(95.9) = 0.17$, $p = .86$), heart rate ($t(90.9) = -0.48$, $p = .63$) at baseline. Similarly, there were no group differences in self-reported trait positive affect ($t(97.0) = -0.98$, $p = .33$), trait negative affect ($t(97.0) = 0.87$, $p = .39$) or reading ability ($t(96.9) = 1.12$, $p = .27$) at baseline (see Table 16 for full baseline characteristics). Because there were no group differences in demographic variables at baseline, no covariates were included in any subsequent statistical models.

4.3.2 Aim 1: Feasibility

Most study participants were able to setup their environment to be consistent with other participants (Table 18). A few study participants had another person in the room with them while completing the study (Control n = 6; Stress n = 2); had a window nearby that did not have a curtain to close to prevent them from looking outside during the task (Control *n* = 1; Stress *n* = 1); used an iPad during the visit instead of a laptop or desktop computer (Control *n* = 2); appeared to not pay attention to baseline videos (Control *n* = 1); had a pet in the room with them during the task (Stress *n* =1); were unable to sit with their feet flat on the floor due to a recent surgery (Control *n* = 1); or experienced distractions during the task, such as background noise (Control *n* = 4; Stress *n* = 4). The feedback survey was administered to all participants and those completing the study twice completed a feedback survey at the end of each study visit. Interestingly, both stress and control participants reported that they believed the experimenters present during the experiment were evaluating them during the task (Control *n* = 29; Stress *n* = 38) even though the control participants were explicitly told that they were not being evaluated. Most of participants, regardless of condition, reported that it was either 'very easy' (Control *n* = 35; Stress *n* = 27) or 'easy' (Control *n* = 10; Stress *n* = 17) to take their own blood pressure during the tasks. While most stress participants did not mind being recorded (*n* = 21), they did also indicate that recording the study visit made them more nervous (*n* = 20; full results reported in Table 18).

4.3.3 Aim 2: Validity

Positive emotion words were only weakly correlated with negative emotion words (range $r = |\ .02 - .41|$), such that two separate ANOVAs were conducted: vigor, wellbeing, and calm were entered together as dependent variables in one model and anxiety, depression, and hostility were entered together as dependent variables into a second model (see Table 19 for correlations between all baseline variables). There was a main effect of group on positive emotions ($Q_N = 26.6$, $p < .001$). Post-hoc analyses demonstrate that control participants reported being calmer and having more vigor relative to stress participants. There was also a main effect of time ($Q_N = 415.2$, $p <$

.001), indicating that participants reported being less calm and having lower well-being during the task relative to the baseline and recovery time points. There were no differences in vigor across time points. Finally, there was also a group x time interaction (Q_N = 81.2, p < .001). Post-hoc analyses suggest that stress participants reported fewer positive emotions, specifically being less calm and having lower wellbeing, during the task compared to control participants (see Table 20 for all *post-hoc* comparisons; see Figure 13 and Figure 14 for changes in self-reported emotions across time by condition).

The model investigating the reactivity of negative emotions during the rTSST revealed a main effect of group (Q_N = 76.0, p < .001), such that control participants reported less anxiety, depression, and hostility relative to stress participants. There was also a main effect of time (Q_N = 299.2, p < .001), suggesting that anxiety, depression, and hostility were highest during the task than at baseline or recovery periods. Finally, there was also a group x time interaction (Q_N = 121.6, p < .001), with post-hoc analyses indicating that stress participants reported more anxiety, depression, and hostility during the task relative to control participants. In addition, participants in the stress condition also continued to report more hostility during the recovery period relative to control participants. See Figure 13, Figure 14, and Figure 15 for graphs depicting changes in self-reported emotions across time by condition and Table 21 all *post-hoc* analyses.

Of the participants who completed a remote visit, only 87 participants had complete cardiovascular data (control n = 47; stress n = 40). Of note, there was a statistical trend towards stress participants having more dropped readings during the rTSST relative to control participants (χ^2(2, N = 99) = 3.55, p = .059; dropped readings: control n = 2; stress n = 9). One control participant was identified as an outlier (>3SD above the mean) for blood pressure data and was not included in the blood pressure analyses. Heart rate was only moderately correlated with both systolic (r = .11) and diastolic blood pressure (r = .38) at baseline. As a result, two separate models were used to evaluate how blood pressure and heart rate changed during the task by condition.

The first model included systolic and diastolic blood pressure as simultaneously dependent variables. There was a main effect of time (Q_N = 245.3, p < .001), such that both systolic and diastolic blood pressure were higher during the speech and mental arithmetic task (but not during speech preparation) relative to baseline and recovery periods. There was also an effect of group (Q_N = 33.8, p <.001), indicating that stress participants had higher blood pressure relative to the control condition. Finally, there was also a significant group x time interaction (Q_N = 31.2, p =.01; Table 22). Post-hoc analyses indicate that participants in the stress condition had higher blood pressure during speech preparation and speech delivery (but not during mental arithmetic) relative to control participants (See Table 22 for all *post-hoc* comparisons).

A repeated measures ANOVA was performed to assess how heart rate changed as a function of group, time, and their interaction during the rTSST. Analyses revealed a main effect of time (F(7, 602) = 73.8, p < .001), such that heart rate was higher during the tasks relative to baseline and recovery periods. There was no main effect of group (F(1, 86) = 3.3, p = .07); however, there was a significant group x time interaction (F(7, 602) = 17.9, p < .001). Post-hoc analyses for the group x time interaction indicate that stress participants had greater heart rate during the speech preparation, speech delivery, and mental arithmetic portions of the task relative to control participants (Table 22 and Figure 15).

4.3.4 Ancillary Aim 1: Reliability of Reactivity

Half of the stress participants (n =25) completed a second study visit, one of which did not have complete physiological data (too many dropped readings), such that data from 24 participants were used for assessing reliability of cardiovascular reactivity and recovery. Four methods were used to calculate the test-retest reliability in cardiovascular reactivity across two study visits: change score, percent change from baseline, area under the curve with respect to ground, and area under the curve with respect to increase. When calculating reactivity separately for the speech preparation, speech delivery, and mental arithmetic tasks, area under the curve approaches demonstrated the highest reliability across all cardiovascular measures (all *ICCs* > 0.60, all *p*s < .001; Table 23). The one exception is that the test-retest reliability of systolic blood pressure reactivity was slightly lower than anticipated during the mental arithmetic task ($ICC_{observed}$ = .56-.58; $ICC_{expected}$ = .60). Averaging reactivity across the three task periods did not increase the reliability for any measure of cardiovascular reactivity (systolic blood pressure, diastolic blood pressure, or heart rate).

4.3.5 Ancillary Aim 2: Reliability of Recovery

Cardiovascular recovery was calculated using six different methods to assess stability across study visits. Of the methods tested, only area under the curve measures demonstrated high test-retest reliability between the study visits for heart rate and blood pressure recovery: area under the curve with respect to ground (AUCg; SBP: *ICC* = .86; DBP: *ICC* = .89; HR: *ICC* = .91), and area under the curve with respect to increase (AUCi; SBP: *ICC* = .87; DBP: *ICC* = .89; HR: *ICC* = .91; Table 23). Unsurprisingly, area under the curve measurements were also highly correlated with one another (*r* = .99). See Table 24 and Table 25 for correlations between all measures of recovery for blood pressure and heart rate, respectively.

4.3.6 Exploratory Aim 1: Task Engagement

There were significant group differences in task engagement ($t(96.0) = -6.58$, $p < .001$), such that participants in the stress condition reported greater average task effort relative to the control condition (Figure 16). When looking at each item of task engagement separately, participants in the stress condition reported greater effort ($t(90.9) = -6.1$, $p < .001$), task difficulty ($t(93.1) = -15.3$, $p < .001$), and fatigue ($t(97.0) = -2.59$, $p = .01$) relative to controls. There were no group differences in self-reported motivation ($t(96.0) = 0.78$, $p = .44$) or importance to perform well on the task ($t(96.8) = -0.62$, $p = .53$). See Table 26 for group means and standard deviations for all measures of task engagement.

4.3.7 Exploratory Aim 2: Trait Positive Affect

Pearson's correlations were used to investigate the relationship between trait positive affect and blood pressure recovery in stress participants during their first rTSST visit. The results indicate that there was no statistically significant correlation between trait positive affect and indices of cardiovascular recovery (rs = -.24 to -.03, all ps > .05). Similarly, there were no significant correlations between trait negative affect and cardiovascular recovery (rs = -.03 to .12, all ps > .05; Table 27).

4.3.8 Exploratory Aim 3: Emotional and Cardiovascular Reactivity

Pearson's correlations were also used to investigate the relationship between emotional reactivity and cardiovascular reactivity. Results suggest that state positive affect (rs = -.22 to -.02, all *p*s > .05) and state negative affect (*r*s = .02 to .26, all *p*s > .05) were both unassociated with cardiovascular reactivity during the rTSST (see Table 28).

4.4 Discussion

The purpose of the final study was to modify the previous rTSST protocol to improve the feasibility, validity, and reliability of the task. Feedback acquired from both research staff and study participants suggests that the modified rTSST can be administered with only a few, minor issues (*e.g.,* participant could not cover a nearby window). The modified rTSST led to both emotional and cardiovascular reactivity during the task in stress participants compared to those in the control condition. Furthermore, we replicated our earlier findings that cardiovascular reactivity and recovery demonstrated high test-retest reliability when calculated by area under the curve measures. A set of secondary aims investigated the relationship between stress physiology and emotional states and traits. Our results do not support prior work demonstrating that trait positive affect associates with more complete blood pressure recovery following a social stressor. The results also indicate that there was no relationship between emotional reactivity and cardiovascular reactivity elicited during the rTSST.

The modified rTSST paradigm successfully induced both emotional and cardiovascular stress reactivity. These findings are in line with recently published work showing that rTSST protocols can elicit changes in self-reported negative emotions (Gunnar et al., 2011; Eagle et al., 2021; Harvie et al., 2021), salivary cortisol and alpha amylase (Gunnar et al., 2011), heart rate (Eagle et al., 2021; Harvie et al., 2021), and heart rate variability (Eagle et al., 2021). We extended this work by demonstrating that a rTSST can also elicit blood pressure reactivity. More specifically, the results indicated that blood pressure was higher in stress participants during the speech preparation and speech delivery tasks, but not during mental arithmetic. This is consistent with in-person TSST protocols, during which, heart rate and blood pressure responses are larger during the speech task relative to the mental arithmetic task (*e.g.*, Al'absi et al., 1997). One potential reason that the speech task elicited a greater blood pressure response than mental arithmetic could be due to factors of social evaluation. As participants were asked to convince the judges that they are the best candidate for their dream jobs, this task likely evoked a greater feeling of evaluation on a topic that is more meaningful (dream job) than performance on a math task. In support of this notion, previous studies demonstrate that interpersonal tasks evoke a stronger cardiovascular response than tasks without an interpersonal component (Christensen & Smith, 1993; Girdler et al., 1990). Taken together, it is not currently recommended to use the mental arithmetic task by itself in the rTSST paradigm when assessing blood pressure responses to acute stress.

In addition to validating the rTSST, the results also indicate good test-retest reliability of cardiovascular reactivity and recovery when assessed one week later. In line with our previous findings from the first rTSST administration, area under the curve methods of calculating reactivity and recovery demonstrate better reliability compared to using change scores or percent change. The previous study also suggested that percent change from baseline was another reliable way to calculate cardiovascular recovery; however, we were unable to replicate those findings. Again, our results indicate that area under the curve approaches might yield more consistent results across test administration. As noted earlier, the main benefit of area under the curve methods is that the trajectory of reactivity and recovery are included in the final measurement, which could indicate overall cardiovascular output during the task relative to the other measures of calculating physiological stress reactivity and recovery. By contrast, the other methods of calculating reactivity and recovery do not yield information about the pattern of change across time, potentially missing some valuable aspects of individual differences in physiological stress responses (*e.g.*, habituation during the tasks). Importantly, these findings have not yet been validated in other types of stress tasks (cognitive or emotional stressors) or across different settings (laboratory-assessed or MRI-based stress tasks). As such, future work is necessary to understand whether area under the curve measures of recovery are consistently reliable across independent samples.

Interestingly, we were unable to replicate meta-analytic findings that trait positive affect was associated with more complete blood pressure recovery (r = -.13; DuPont et al., 2020). Our results suggest that trait positive affect is unrelated to blood pressure recovery (SBP r = .02; DBP r = -.22; both ps > .05). Of note, the relationship between diastolic blood pressure recovery and trait positive affect are in the proposed direction and of a magnitude larger than we might expect, albeit not statistically significant after Bonferroni correction. This is especially surprising given that the meta-analytic findings suggested that social stressors, like the TSST, were more likely to demonstrate this relationship compared to cognitive or emotional stress tasks (DuPont et al., 2020). Importantly, the most commonly used measure to assess trait positive affect in the meta-analysis was the Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988). The positive affect scale of the PANAS includes items like interested and strong, which are not considered true measures of positive affect. In addition, the PANAS does not include indicators of positive affect across the continuum of arousal, which may be particularly important when associating affect with physiology. As such, further work is necessary to confirm whether trait positive affect, when measured across the continuum of arousal, still correlates with more complete blood pressure recovery.

Finally, we also evaluated the relationship between emotional and cardiovascular reactivity. A greater decrease in positive affect during the task was associated with higher diastolic blood pressure during the task, albeit not significantly after Bonferroni correction. Interestingly, task-related changes in diastolic blood pressure were more strongly correlated with changes in positive affect (r = -.24) relative to changes in negative affect (r = .12). The results are of a similar magnitude of previous studies investigating how negative emotional states associate with physiological stress reactivity (r = .13 - .34; Feldman et al., 1999). The fact that state positive affect may be more strongly correlated with stress physiology than negative affect is important as many studies only report on negative emotions. Neglecting to measure stress-related changes in positive affect could provide an incomplete picture of how emotional states impact co-occurring changes in physiology.

In summary, the current study extends previous research to demonstrate that rTSST protocols can also be used to assess cardiovascular (blood pressure and heart rate) responses that are reliable when measured one week later.

5.0 General Discussion

The overarching aim of the current study was to test whether a positive psychological intervention could facilitate blood pressure recovery following a psychological stressor. Unfortunately, the study aims were unable to be fully tested because the positive psychological intervention did not increase positive affect as predicted (Study 1) and the initial remote Trier Social Stress Test (rTSST) did not evoke greater cardiovascular reactivity during the stress task relative to a control condition (Study 2). Instead of pursuing the original study aim, the final study was aimed at modifying the rTSST so that it elicited both emotional and cardiovascular reactivity (Study 3).

Although we were unable to directly test our study hypotheses, a single (unpublished) study has examined whether a positive psychological intervention delivered over multiple weeks could influence stress physiology (Leclerc, 2007). Leclerc (2017) tested whether completing a Three Good Things gratitude intervention for one month would lead to lower cortisol reactivity following a video game stressor. Unfortunately, the laboratory stress task failed to elicit cortisol stress reactivity as cortisol *decreased* from baseline to 20 minutes after task onset. As such, the study was unable to test whether increasing global levels of gratitude are able to alter stress physiology. Therefore, it still unknown how increasing positive emotions by implementing a positive psychological intervention can alter acute stress physiology.

Positive psychological interventions are unique in that they purposefully aim to increase the frequency, duration, and/or intensity of positive emotions. However, other skills that fall under the umbrella of positive psychology, such as mindfulness (Rusk & Waters, 2013), have also been shown to increase positive affect. Mindfulness includes awareness of the present moment and acceptance of present-moment experiences as they arise (Lindsay & Creswell, 2019). While mindfulness explicitly *does not* aim to alter emotional states, but rather to notice and accept emotional states at they arise, numerous studies now suggest that mindfulness interventions can increase global measures of positive affect (Nyklíček & Kuijpers, 2008; Howells, Ivtzan, & Eiroa-Orosa, 2016; Fredrickson et al., 2017; Bower et al., 2015) and daily reports of positive affect (Lindsay et al., 2018). Furthermore, there are now numerous studies investigating whether mindfulness interventions alter physiology during acute laboratory stressors. The overwhelming majority of studies suggest that mindfulness interventions associate with reduced cortisol reactivity (Lindsay et al., 2018b; Hopkins et al., 2016; Klaperski et al., 2014; but also see Drogos et al., 2021; Creswell et al., 2014). However, the evidence for the effects of mindfulness on cardiovascular responses to stress remain mixed, with some studies suggesting that mindfulness reduces reactivity (Lindsay et al., 2018; Nyklíček et al., 2013), or facilitates recovery (Nyklíček et al., 2013), while other studies report null findings (Drogos et al., 2021; Creswell et al., 2014). As such, it remains plausible that mindfulness interventions may alter cortisol responses to acute stressors, at least in part, by their ability to enhance positive affect.

Although we were unable to test our overall study hypotheses, we were able to establish a rTSST protocol that induced emotional and cardiovascular reactivity. To date, there are only three such studies that have created and implemented a rTSST (Harvie et al., 2021; Gunnar et al., 2021; Eagle et al., 2021). Gunnar and colleagues (2021) were the first published study to create a rTSST protocol and demonstrated that cortisol and alpha-amylase, a marker of sympathetic activation, increase during an online stress task in an adolescent sample. The second published study extended these findings to show that heart rate increases while heart rate variability decreases during the rTSST. Furthermore, rTSST-evoked changes in heart rate and heart rate variability did not habituate when the task was repeated 12 weeks later (Eagle et al., 2021). Critically, neither of these studies included a control condition. Without comparing the stress protocol to a control condition, it is difficult to establish whether the stressful components of the task (*e.g.*, social evaluation, time pressure, novelty) contribute to the physiological responses during the task above and beyond other, irrelevant factors, such as rate and rhythm of speech, interacting with unfamiliar researchers on Zoom, or cognitive effort exerted during the task. In fact, in our initial rTSST protocol (Study 1), stress participants did exhibit blood pressure and heart rate reactivity to the task; however, these responses were not stronger than cardiovascular responses in the control condition. This would suggest that cardiovascular responses to the rTSST could not be attributed to the stressful components of the task. In light of these findings, a control condition is crucial to assess whether the physiological changes occur due to the stressful nature of the task, or other psychological and cognitive factors engaged during the task. To address these concerns, Harvie and colleagues (2021) used a control condition to establish that their rTSST led to greater heart rate reactivity relative to a control task. Interestingly, this study used a smart phone application to measure heart rate by photoplethysmography, demonstrating that the rTSST can be administered cheaply and to a wider geographical audience, without the laboratory having to mail study equipment to participants (Harvie et al., 2021). In summary, although the literature on rTSSTs remains nascent, accumulating evidence suggests that laboratory stressors can be delivered online without sacrificing the ability to evaluate their physiological sequelae.

The current study extends the findings from the rTSST literature in three important ways: by (1) including blood pressure responses to the rTSST, (2) replicating findings that the rTSST has good test-retest reliability, and (3) exploring the test-retest reliability of various methods for calculating recovery. Although it is more common to collect cortisol and heart rate measures during the TSST, extending this work to include blood pressure may be of particular interest to researchers studying the relationship between stress and cardiovascular disease risk. In fact, blood pressure responses to acute laboratory stressors are prospectively associated with negative cardiovascular outcomes (Chida & Steptoe, 2010; Turner et al., 2020), particularly when paired with low heart rate reactivity (Brindle et al., 2016). Thus, validating a rTSST protocol for blood pressure responses to stress may allow researchers interested in understanding the relationship between psychological stress and cardiovascular disease risk to extend their work to populations they might not otherwise reach (*e.g.*, international, remotely rural, transportation issues, etc; Kirschbaum 2021). The second benefit of the current study is that we replicated prior work demonstrating that the rTSST paradigm elicits a cardiovascular response with high test-retest reliability (Eagle et al., 2020). Our findings are in line with prior work indicating that cardiovascular responses to psychological stress show a lesser degree of habituation relative to cortisol reactivity (Hughes, Lü, & Howard, 2018), suggesting that researchers can use rTSST paradigms for repeated measures of acute stress. Finally, a longstanding issue in the field of stress reactivity is a lack of consensus on how to calculate physiological recovery following an acute stressor. In fact, many studies report collecting recovery without reporting on such findings, likely due, at least in part, to the lack of consensus on how to best measure recovery (Linden et al., 1997). Although there has been a qualitative review on the various modes of calculating recovery (Linden et al., 1997), no studies to date have quantitatively compared these methods. As such, the current study extends prior research by showing, over the course of two studies, that area under the curve metrics are the most reliable measures of calculating recovery to a stressor. The aim of reporting these results is to generate further discussion and consensus in the field, such that studies conducted using different tasks (cognitive and emotional stressors) and across various contexts (remote, MRI, laboratory) can work towards a common method of calculating and reporting recovery.

While the current study was unable to compare responses to the rTSST with an in-person protocol, the magnitude of the responses elicited during the tasks are comparable to in-person reports. During in-person TSSTs, heart rate typically increases by 15-25 bpm during the task (Kudiekla, Hellhammer, & Kirschbaum, 2007). Previous rTSST paradigms elicit a heart rate response between 2-7 bpm, which is considerably lower than anticipated (Eagle et al., 2021; Harvie et al., 2021). By contrast the current rTSST protocol led to a larger increase in heart rate that more closely aligns to in-person reports (11-16 bpm). The current rTSST protocol deviated from the two previously published reports in a few (seemingly minor) ways that could have led to larger increases in heart rate. One reason could be because the current rTSST placed participants into breakout rooms (similar to Gunnar et al., 2021) with two judges, who were present during the speech preparation period. By contrast, both prior studies left the participant alone during the preparation period and kept the participant in the main Zoom room during the entire procedure (Eagle et al., 2021; Harvie et al., 2021). As mentioned earlier (Study 2: Discussion), sending participants into a breakout room could lead to a sense of novelty. In fact, previous work demonstrates that providing participants more time to habituate to the laboratory environment prior to an acute stressor reduces cortisol reactivity (Goodman, Janson, & Wolf, 2017). Although it is unclear whether these effects hold using cardiovascular measures of stress reactivity, it is possible that leaving participants in the main Zoom room throughout that duration of the experiment could reduce the degree of reactivity to the task. Another difference between the current study and previously published rTSSTs is whether participants were able to view themselves during the study tasks. The current study asked stress participants to hide their own image so that they were could fully attend to the judges rather than focusing on their own image during the tasks, as this could be used a way to distract themselves or cope with the stress of performing the study tasks. By contrast the two other rTSST paradigms that measured heart rate did not provide instructions regarding the participants' own video, potentially providing the participants with a means of averting their attention away from the judges.

In person, the TSST typically increases systolic blood pressure by 15-30 mmHg (al'Absi et al., 1997; al'Absi et al., 2012; Girdler et al., 1990) and diastolic blood pressure by 10-20 mmHg (al'Absi et al., 1997; al'Absi et al., 2012; Girdler et al., 1990). By comparison, virtual reality versions of the TSST show smaller blood pressure responses to the task than in-person reports (Δ SBP ~10 mmHg; Hawn et al., 2015). Blood pressure reactivity in our version of the rTSST exhibited changes in systolic (11-20 mmHg) and diastolic (8-17mHg) blood pressure that are between those reported for in-person and virtual reality TSST protocols. One potential explanation as to why the rTSST elicited smaller blood pressure responses than in-person stressors could be due to the fact that participants completed the rTSST from the comfort of their own home. In fact, 57% of the stress participants (Study 3) noted that they imagined the stress tasks would be more difficult and/or stressful in-person relative to an online task. As mentioned above, novelty is an important aspect of acute psychological stress paradigms that could have reasonably influenced the blood pressure responses during the rTSST.

Although the current study has several strengths, including the pre-registration of all data collection procedures and statistical analyses, assessing heart rate *and* blood pressure during the rTSST, evaluating test-retest reliability of the task, and measuring positive and negative emotions along the arousal continuum, it is not without its limitations. First, all three studies are limited to an undergraduate sample, making it unclear how this might generalize to older samples. Expanding upon this limitation is the fact that all data were collected during the COVID-19 pandemic. As research demonstrates that chronic stress can influence acute stress reactivity (Chida & Hamer, 2008), it is plausible that greater perceived stress, as a result of the pandemic, could have influenced the data. Second, due to the ongoing pandemic, we were unable to bring participants into the laboratory to compare in-person stress responses relative to the remote protocol, making it unclear whether the rTSST leads to smaller magnitudes of within-individual differences in cardiovascular reactivity relative to in-person procedures. Third, although all stress participants were invited to complete a second study visit, half of the participants in the final study declined to complete a second study visit. Because participants self-selected to complete a second visit, it is possible that those who perceived the task as less stressful were more likely to participate in a second study visit, which could have influenced the estimated test-retest reliability.

In light of these limitations, future studies are needed to expand upon the current findings. As the overall study aim was unable to be tested, other work is necessary to understand how increasing global positive affect by a positive psychological intervention might influence stress physiology. To expand upon the rTSST, the findings suggesting that test-retest reliability of cardiovascular reactivity and recovery are highest when measured using area under the curve metrics should be tested in other samples and expanded to include additional stress paradigms (*e.g.,* in-person laboratory stressors, cognitive tasks, etc). In addition, once it is safe to perform the TSST again in person, it would also be beneficial to determine whether those who exhibit high cardiovascular responses during the rTSST show similarly high reactivity during an in-person version of the TSST. In continuing to develop and refine a rTSST paradigm that reliability evokes a cardiovascular response, stress researchers will be able to include populations that were previously unable to participate, making findings in the field more generalizable and inclusive.

6.0 Tables

Table 1. List of questionnaires and the time point(s) of administration

Questionnaires	Baseline 1	Baseline 2	Post-Activity	Post-PPI 1	Post-PPI 2
Demographics					
Age	X				
Sex/Gender Identity	X				
Race/Ethnicity	X				
Socioeconomic Status					
Parental education		X			
Perceived social standing		X			
Psychiatric History					
Psychiatric medication use		X			
PROMIS-ANX-SF	X			X	
PROMIS-DEP-SF	X			X	
Hedonic Well-being					
In General					
Pos/Neg Emotional Style Scale	X				X
Pos and Neg Affect Schedule	X				X
Last Few Days					
Pos/Neg Emotional Style Scale	X			X	
Pos and Neg Affect Schedule	X			X	
PROMIS- Life Satisfaction		X			X
Other Well-being					
Psychological well-being scale	X			X	
Life Orientation Test – revised		X			X
Social Factors					
UCLA Loneliness Scale		X	X		X
Interpersonal Support Evaluation List		X			X
Stress					
Perceived Stress Scale		X	X	X	
Academic Stress			X		
Health Behaviors					
Sleep Quality and Duration		X	X		X
Physical Activity		X	X		X

Note. Questionnaires administered post-activity consist of fewer items, except for the Positive and Negative Affect Schedule and Positive and Negative Emotional Style Scale. Citations for each questionnaire can be found in the main text.

Table 2. Participant demographic information and baseline characteristics for the positive psychological intervention (Study 1).

	Controls (N = 122)	Intervention (N = 103)	Difference	
	M (*SD*) *or N* (*%*)	*M* (*SD*) *or N* (*%*)	t or X^2	p
Age	18.7 (1.1)	18.8 (2.8)	-0.58	0.56
Sex				
Female	91 (74.6%)	82 (79.6%)	0.53	.46
Male	31 (25.4%)	21 (20.4%)		
Race				
Caucasian	85 (69.7%)	60 (58.3%)		
Asian	26 (21.3%)	25 (24.3%)	5.58	.23
African American	4 (3.3%)	7 (6.8%)		
Biracial	5 (4.1%)	10 (9.7%)		
Other	2 (1.6%)	1 (1.0%)		
Year in College				
Freshman	81 (66.4%)	73 (70.9%)		
Sophomore	23 (18.9%)	18 (17.5%)	2.02	.73
Junior	11 (9.0%)	8 (7.8%)		
Senior / Senior +	7 (5.7%)	4 (3.9%)		
Psychotropic Use				
Yes	17 (13.9%)	7 (6.8%)	2.28	.13
No	105 (86.1%)	96 (93.2%)		
Hedonic Well-being				
PANAS-PA: In general	33.7 (6.08)	33.5 (6.10)	0.21	.83
PANAS-PA: Last few days	31.1 (7.43)	31.1 (7.75)	.006	.99
PES: In general	27.8 (5.73)	28.7 (5.68)	-1.28	.20
PES: Last few days	16.6 (6.63)	17.3 (7.18)	-0.80	.43
Life Satisfaction	40.9 (9.51)	39.7 (9.96)	0.93	.35
Other Well-being				
Eudaimonic well-being	216 (32.1)	212 (31.8)	0.97	.33
Optimism	19.4 (4.35)	19.7 (4.05)	-0.44	.66
Negative Affect				
PANAS-NA: In general	20.3 (6.08)	20.1 (5.74)	0.22	.83
PANAS-NA: Last few days	18.6 (5.87)	18.9 (5.56)	-0.39	.70
NES: In general	17.5 (5.26)	17.3 (5.35)	0.28	.77
NES: Last few days	7.35 (5.33)	7.86 (5.37)	-0.71	0.48
PROMIS-ANX	16.9 (5.21)	17.3 (4.96)	-0.58	.56
PROMIS-MDD	13.8 (6.08)	13.6 (5.12)	0.31	.76
Perceived Stress	17.9 (6.05)	18.7 (5.70)	-0.99	.32
Social Factors				
ISEL (Perceived Social Support)	39.8 (5.81)	38.4 (6.71)	1.66	.09
UCLA Loneliness Scale	10.1 (4.85)	10.8 (4.76)	-0.96	.33
Health Behaviors				
Sleep duration (min)	458 (59.1)	461 (58.8)	-0.35	.73
Sleep quality (1 – 5)	2.61 (0.87)	2.57 (0.86)	0.29	.77
Light physical activity (min)	270 (281)	340 (758)	-0.88	.38
Vig-mod physical activity (min)	119 (172)	142 (191)	-0.97	.33

Table 3. Correlations between study variables at baseline (Study 1).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. PA- Gen	-														
2. PA- Days	.76	-													
3. PES- Gen	.71	.61	-												
4. PES- Days	.62	.79	.75	-											
5. GLS	.41	.51	.37	.55	-										
6. PWB	.57	.65	.44	.56	.60	-									
7. LOT-R	.46	.47	.45	.50	.58	.63	-								
8. NA- Gen	-.13	-.25	-.24	-.27	-.26	-.43	-.33	-							
9. NA- Days	-.14	-.26	-.24	-.29	-.28	-.43	-.27	.79	-						
10. NES-Gen	-.25	-.33	-.34	-.38	-.36	-.48	-.36	.84	.73	-					
11. NES- Days	-.26	-.38	-.34	-.40	-.40	-.51	-.38	.68	.84	.77	-				
12. ANX	-.21	-.33	-.32	-.37	-.30	-.50	-.30	.71	.76	.70	.73	-			
13. MDD	-.39	-.49	-.40	-.47	-.53	-.64	-.47	.53	.61	.63	.71	.67	-		
14. PSS	-.35	-.47	-.36	-.50	-.48	-.58	-.47	.55	.63	.54	.61	.65	.62		
15. ISEL	.34	.36	.34	.32	.31	.53	.39	-.27	-.23	-.26	-.26	-.18	-.31	-.25	
16. UCLA	-.42	-.49	-.41	-.45	-.38	-.66	-.53	.39	.36	.41	.45	.42	.47	.45	-.70

Notes. Bolded values are statistically significant at $p < .05$ after Bonferroni correction. The colors on the table represent the difference clusters of study variables that were simultaneously entered as dependent variables within the same model. *Abbreviations.* PA-gen = PANAS-PA (in general); PA-Days = PANAS-PA (last few day); PES-Gen = Positive emotional style (in general); PES-Days = Positive emotional style (last few days); GLS = PROMIS- General Life Satisfaction; PWB = Psychological Well-being Scale; LOT-R = Life Orientation Test- Revised; NA-gen = PANAS-NA (in general); NA-Days = PANAS-NA (last few day); NES-Gen = Negative emotional style (in general); NES-Days = Negative emotional style (last few days); ANX = PROMIS-Anxiety-Short-Form; MDD = PROMIS-Depression-Short Form; PSS = Perceived Stress Scale; ISEL = Interpersonal Support Evaluation List; UCLA = UCLA Loneliness Scale.

Table 4. Estimated effect size for each positive psychological activity (Study 1).

Activity	Effect size (*d*)	Citation(s)
Savoring	0.25 – 0.65	Smith et al., 2014
Signature strengths	0.29 – 0.73	Proyer, et al., 2015; Seligman et al., 2005
Three good things	0.15 – 0.72	Seligman et al., 2005; Mongrain & Anselmo-Matthews, 2012
Gratitude letter	0.34 – 1.09	Kumar & Epley, 2018; Lyubomirsky et al., 2011
Acts of kindness	0.30 – 1.25	Otake et al., 2006; Curry et al., 2018
Future best self	0.23 – 0.93	Seligman et al., 2005; Meevissen et al., 2011

Table 5. List of pre-visit restrictions (Study 2).

No food in the past 3 hours
No beverages (except for water) within the last 30 minutes
No caffeine in the last 3 hours
No moderate to vigorous exercise in the last 2 hours
No alcohol within the past 12 hours
No symptoms of viral illness or cold (e.g., fever, shortness of breath, chills, etc.)

Table 6. One-item questions assessed immediately following each stress task (Study 2).

Item	Question	Scales		
Positive	How positive do you feel during the task?	Not positive	-	Very positive
Negative	How negative do you feel during the task?	Not negative	-	Very negative
Arousal	How calm or excited did you feel during the task?	Calm	-	Excited
Fatigue	How mentally tired do you feel right now?	Not at all		Extremely
Motivation	How motivated were you to perform well on the task?	Unmotivated	-	Motivated
Importance	How important is it for you to perform well on the task?	Unimportant	-	Important
Difficulty	How difficult was it for you to succeed on the task?	Very easy	-	Very difficult
Effort	How much effort did you use towards the task?	No effort	-	A lot of effort

Note: Study 1 only includes measures the following measures: positive, negative, and arousal. The full list of items will be presented during Study 2. Questions related to fatigue, motivation, importance, difficulty, and effort were adapted from: Richter, Friedrich, & Gendolla, 2008; Wright et al., 2007; Wright, Martin, & Bland, 2003.

Table 7. Participant demographic information and baseline characteristics for the remote TSST (Study 2).

	Controls (N = 32)	Stress (N = 37)	Difference	
	M (*SD*) *or N* (*%*)	*M* (*SD*) *or N* (*%*)	t or X^2	p
Demographic Information				
Age	19.4 (4.77)	18.2 (0.60)	1.41	.17
Sex				
Female	24 (75.0%)	27 (73.0%)	<0.01	1.0
Male	8 (25.0%)	10 (27.0%)		
Race				
Caucasian	24 (75.0%)	24 (64.9%)		
Asian	6 (18.8%)	8 (21.6)	4.28	.37
African American	-	3 (8.1%)		
American Indian	1 (3.1%)	-		
Other	1 (3.1%)	2 (5.4%)		
Year in College				
Freshman	19 (59.4%)	14 (37.8%)		
Sophomore	5 (15.6%)	2 (5.4%)	2.99	.39
Junior	3 (9.4%)	-		
Senior / Senior +	1 (3.1%)	-		
Missing	4 (12.5%)	21 (56.8%)		
Psychotropic Use				
Yes	3 (9.4%)	5 (13.5%)	0.03	.87
No	29 (90.6%)	32 (86.5%)		
Baseline Characteristics				
SBP (mmHg)	113 (10.4)	109 (10.3)	1.69	.10
DBP (mmHg)	68.9 (11.3)	65.1 (6.67)	1.62	.11
HR (bpm)	72.3 (12.9)	74.3 (10.4)	-0.68	.50
Positivity (0 – 100 scale)	66.3 (13.6)	65.5 (18.2)	0.19	.85
Negativity (0 – 100 scale)	28.5 (18.7)	32.3 (21.4)	-0.78	.44
Calm (0 – 100 scale)	69.1 (17.3)	70.9 (18.3)	-0.44	0.67
Anxiety (0 – 100 scale)	36.3 (19.4)	38.0 (25.5)	-0.32	0.75

Table 8. Researcher documented issues that arose during the remote TSST and participant responses to the feedback survey (Study 2).

Issues Documented	*N* of Reports	
	Control	Stress
Technical Issues		
Participant could not hide their self-view	1	1
Zoom session was unable to be recorded	1	0
Difficulty fitting blood pressure cuff properly resulting in poor BP data	2	0
Poor internet connection	2	1
Could not print blood pressure readings	1	0
Non-compliance		
Roommate was present during task	5	1
Pet was in the room	2	0
Difficulty remaining still during either baseline, tasks, or recovery	1	3
Cell phone use or received SMS on computer during visit	1	1
Did not close all browsers (*e.g.*, heard email ping in the background)	1	0
Unable to cover nearby windows	0	1
Unknown distraction (*e.g.*, suspected phone use, background noise)	2	4

Participant Survey Responses	*N* (%) of Reports
Did you believe judges were trained to assess the speech?	
Yes	16 (84.2%)
No	3 (15.8%)
How might these tasks compare to performing them in person?	
In-person would be worse	9 (47.4%)
Online would be worse	4 (21.1%)
Online is likely more distracting	2 (10.5%)
No difference	4 (21.1%)
Do you think it was more difficult/stressful on Zoom (vs in-person)?	
More stressful	5 (26.3%)
Less stressful	10 (52.6%)
No difference	4 (21.1%)
How did you feel about having the Zoom session recorded?	
Did not mind	14 (73.7%)
Did not prefer it	2 (10.5%)
Made me feel nervous	3 (15.8%)
How easy or difficult was it for you to take your own blood pressure?	
Easy	16 (84.2%)
Measurements were easy, fitting cuff was tricky	3 (15.8%)

Table 9. Correlations between cardiovascular measures and self-reported emotions at baseline (Study 2).

	SBP	DBP	HR	Positivity	Calm	Negativity
SBP						
DBP	.67***					
HR	.07	.45***				
Positivity	.08	-.08	-.06			
Calm	-.10	-.26*	-.18	.58***		
Negativity	.03	.11	.14	-.84***	-.48***	
Anxious	-.05	.06	.02	-.53***	-.65***	.58***

Notes. * p <.05, ** p < 0.01, *** p < .001 after Bonferroni correction; SBP = systolic blood pressure (mmHg); DBP = diastolic blood pressure (mmHg); HR = heart rate (bpm); all self-reported emotions are on a 0 (low) – 100 (high) scale.

Table 10. Means, standard deviations, and post-hoc p-values for emotional reactivity during the rTSST (Study 2)

Main Effects												
	Positivity			Calm			Negativity			Anxiety		
	M	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*	*p*
Time												
Baseline	65.7	16.4	<.001	69.2	17.5	<.001	31.2	20.0	<.001	38.2	22.4	<.001
Task	44.6	26.9	-	39.8	26.3	-	48.1	27.2	-	59.4	27.2	-
Recovery	59.4	16.7	<.001	70.5	19.2	<.001	31.3	19.7	<.001	30.1	20.8	<.001
Group												
Control	63.3	16.5	<.001	65.5	20.7	.002	28.2	18.7	<.001	33.9	20.5	<.001
Stress	50.1	25.2		54.3	28.5		45.3	25.7		50.9	29.1	
Group*Time Interactions												
	Positivity			Calm			Negativity			Anxiety		
	Control	Stress	*p*	Control	Stress	*p*	Control	Stress	*p*	Control	Stress	*p*
Time												
Baseline			.99			0.99			.85			.99
M	66.3	65.1		69.1	69.2		28.5	33.9		36.3	40.1	
SD	13.6	18.8		17.3	17.9		18.7	21.2		19.4	25.1	
Task			<.001			<.001			<.001			<.001
M	62.2	27.6		52.1	27.9		37.8	64.0		41.5	76.6	
SD	18.3	22.7		20.9	25.7		19.7	25.2		20.3	21.3	
Recovery			.99			.13			.01			.05
M	61.3	57.5		75.3	65.8		24.4	38.0		23.9	36.1	
SD	17.3	16.2		16.8	20.4		17.4	19.7		18.1	21.7	

Note. all *p*-values reported are Bonferroni corrected. All *p*-values for the main effect of time are relative to task values. Bolded values are statistically significant.

Table 11. Means, standard deviations, and post-hoc p-values for physiological reactivity during the rTSST (Study 2)

Main Effects									
	SBP			DBP			HR		
	M	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*	*p*
Time									
Baseline	110.3	9.8	<.001	66.4	8.6	<.001	73.0	11.0	<.001
Speech	123.3	13.3	-	78.0	9.5	-	83.2	11.8	-
Math	122.9	12.8	-	75.5	9.3	-	80.4	11.6	-
Recovery 1	113.1	10.5	<.001	68.5	8.1	<.001	71.4	9.9	<.001
Recovery 2	110.6	10.1	<.001	67.1	7.5	<.001	72.3	10.7	<.001
Recovery 3	110.1	10.3	<.001	66.6	7.7	<.001	72.7	10.3	<.01
Recovery 4	109.2	9.9	<.001	67.3	8.1	<.001	73.5	10.8	<.001
Group									
Control	115.0	12.3	ns	71.0	10.3	ns	73.0	11.2	ns
Stress	115.0	14.1		69.6	9.9		77.0	11.7	

Group*Time Interactions									
	SBP			DBP			HR		
	Control	Stress	*p*	Control	Stress	*p*	Control	Stress	*p*
Time									
Baseline			ns			ns			.99
M	112.1	108.8		68.0	65.4		71.3	72.3	
SD	8.9	10.3		10.4	6.7		11.7	10.4	
Speech			ns			ns			.28
M	120.1	125.9		76.5	79.2		79.8	85.8	
SD	10.0	15.1		8.9	9.9		11.6	11.4	
Math			ns			ns			.02
M	119.7	125.4		73.7	76.9		75.7	84.1	
SD	8.9	14.8		7.3	10.5		10.5	11.1	
Recovery			ns			ns.			.99
M	112.7	113.5		69.0	68.1		69.9	72.6	
SD	8.0	12.3		8.0	8.2		9.4	10.2	

Note. all *p*-values reported are Bonferroni corrected. All *p*-values for the main effect of time are relative to task values. ns denotes when the omnibus test was not statistically significant and therefore post-hoc analyses were not performed. Bolded values are statistically significant.

Table 12. Intra-class correlations for all measures of reactivity and recovery (Study 2).

	Systolic BP			*Diastolic BP*			*Heart Rate*		
	ICC	95% CI	*p*	ICC	95% CI	*p*	ICC	95% CI	*p*
Reactivity									
Speech Task									
Change score	.11	[-.28, .46]	.29	-.11	[-.47, .28]	.70	.60	[.30, .79]	<.001
Percent	.06	[-.33, .42]	.38	-.20	[-.54, .19]	.84	.56	[.25, .76]	<.001
AUCg	.83	[.67, .92]	<.001	.81	[.64, .91]	<.001	.72	[.49, .86]	<.001
AUCi	.81	[.64, .91]	<.001	.80	[.61, .91]	<.001	.73	[.50, .86]	<.001
Math Task									
Change score	.32	[-.03, .61]	.03	.01	[-.37, .38]	.48	.57	[.24, .78]	<.001
Percent	.25	[-.12, .56]	.09	-.08	[-.45, .31]	.65	.55	[.22, .77]	.001
AUCg	.88	[.74, .94]	<.001	.67	[.41, .83]	<.001	.72	[.47, .86]	<.001
AUCi	.87	[.73, .94]	<.001	.66	[.39, .83]	<.001	.72	[.48, .86]	<.001
Average									
Change score	.27	[-.10, .57]	.08	-.01	[-.38, .36]	.52	.72	[.48, .86]	<.001
Percent	.19	[-.20, .52]	.17	-.12	[-.48, .27]	.73	.68	[.42, .84]	<.001
AUCg	.84	[.68, .92]	<.001	.80	[.62, .90]	<.001	.76	[.54, .88]	<.001
AUCi	.81	[.63, .91]	<.001	.77	[.55, .88]	<.001	.77	[.56, .89]	<.001
Recovery									
CS- baseline	.25	[-.11, .56]	.09	-.08	[-.45, .30]	.66	.56	[.23, .77]	<.001
CS- task	.15	[-.24, .48]	.23	-.05	[-.42, .32]	.60	.58	[.28, .78]	<.001
PC- baseline	.79	[.60, .90]	<.001	.69	[.44, .84]	<.001	.79	[.59, .89]	<.001
PC- task	.26	[-.08, .55]	.07	.11	[-.25, .45]	.27	.60	[.31, .79]	<.001
AUC- ground	.87	[.73, .94]	<.001	.80	[.60, .91]	<.001	.74	[.48, .88]	<.001
AUC- increase	.86	[.71, .94]	<.001	.79	[.58, .90]	<.001	.72	[.46, .87]	<.001

Note. All ICCs were calculated as 2-way mixed effects models with absolute agreement. Bolded items meet our predictions of ICC $\geqq$ .60. Abbreviations: CS = change score; PC = percent change; AUC = area under the curve.

Table 13. Correlations between study visits using various methods of measuring blood pressure recovery (Study 2).

		Visit 1						Visit 2					
		Diastolic Blood Pressure Recovery											
		1	2	3	4	5	6	7	8	9	10	11	12
Visit 1	1. CS-B		.38	.19	.45	.02	-.07	-.15	-.25	.04	.14	-.05	-.05
	2. CS-T	.67		.16	-.26	.33	.37	.09	.06	.27	.11	.21	.19
	3. PC-B	.52	.29		.61	.89	.85	.00	.36	.76	-.14	.81	.81
	4. PC-T	.69	.19	.76		.19	.10	-.17	-.03	.29	-.08	.33	.33
	5. AUCg	.29	.32	.88	.36		.99	.09	.45	.77	-.12	.81	.80
	6. AUCi	.17	.28	.83	.26	.99		.11	.47	.76	-.13	.81	.80
Visit 2	7. CS-B	.30	.00	.25	.22	.22	.17		.25	.40	.59	.09	.00
	8. CS-T	.18	.28	.40	.21	.42	.42	.37		.38	-.40	.58	.61
	9. PC-B	.30	.10	.81	.45	.83	.80	.37	.25		.25	.84	.79
	10. PC-T	.37	.12	.19	.17	.17	.12	.56	-.23	.49		-.31	-.40
	11. AUCg	.17	.04	.84	.44	.87	.86	.21	.39	.92	.11		.99
	12. AUCi	.16	.05	.83	.43	.87	.86	.12	.41	.89	.04	.99	
		Systolic Blood Pressure Recovery											

Note. The bottom half of the correlation matrix are the correlations for systolic blood pressure whereas the top half are the correlations for diastolic blood pressure. Bolded values are statistically significant at $p < .05$ after Bonferroni correction. CS-B: change score from baseline; CS-T: change score from task; PC-B: percent change from baseline; PC-T: percent change from task; AUCg: area under the curve with respect to ground; AUCi: area under the curve with respect to increase; For CS-T and PC-T measures, smaller numbers reflect poorer recovery. For all other measures, smaller numbers represent better recovery.

Table 14. Correlations between study visits using various methods of measuring heart rate recovery (Study 2).

		Visit 1						Visit 2				
		1	2	3	4	5	6	7	8	9	10	11
Visit 1	1. CS-B											
	2. CS-T	.47										
	3. PC-B	.19	.10									
	4. PC-T	.74	.00	.41								
	5. AUCg	-.18	.11	.86	-.11							
	6. AUCi	-.27	.11	.81	-.20	.99						
Visit 2	7. CS-B	.52	.25	.26	.54	-.03	-.10					
	8. CS-T	.47	.70	.08	.19	-.03	-.05	.33				
	9. PC-B	.21	.23	.80	.32	.69	.63	.32	.01			
	10. PC-T	.38	-.06	.34	.60	.04	-.04	.82	-.08	.45		
	11. AUCg	.03	.28	.70	.03	.75	.73	-.08	.04	.88	-.04	
	12. AUCi	.01	.29	.68	-.01	.74	.73	-.15	.05	.84	-.11	.99

Note. Bolded values are statistically significant at $p < .05$ after Bonferroni correction. CS-B: change score from baseline; CS-T: change score from task; PC-B: percent change from baseline; PC-T: percent change from task; AUCg: area under the curve with respect to ground; AUCi: area under the curve with respect to increase; For CS-T and PC-T measures, smaller numbers reflect poorer recovery. For all other measures, smaller numbers represent better recovery.

Table 15. Mean and standard deviation of self-reported task engagement by group (Study 2).

	Control	Stress	Difference	
	M (*SD*)	*M* (*SD*)	*t-statistic*	*p-value*
Fatigue	43.0 (23.5)	59.9 (23.4)	-2.96	.004
Motivation	66.6 (15.4)	59.4 (25.6)	1.42	.16
Task Importance	53.8 (26.6)	56.0 (27.5)	-0.34	.73
Task Difficulty	27.8 (14.9)	72.4 (19.3)	-10.73	<.001
Task Effort	53.9 (21.0)	74.5 (16.9)	-4.42	<.001
Average Effort	49.0 (15.2)	64.4 (16.2)	-4.04	<.001

Table 16. Participant demographic information and baseline characteristics for the remote TSST (Study 3).

	Controls (N = 50)	Stress (N = 49)	Difference	
	M (*SD*) *or N* (*%*)	*M* (*SD*) *or N* (*%*)	*t* or X^2	*p*
Demographic Information				
Age	19.2 (1.19)	20.3 (4.82)	-1.56	.12
Sex				
Female	27 (54.0%)	27 (55.1%)	<0.01	1.0
Male	23 (46.0%)	22 (44.9%)		
Race				
Caucasian	34 (68.0%)	33 (67.3%)		
Asian	11 (22.0%)	10 (20.4%)	3.05	.55
African American	4 (8.0%)	2 (4.1%)		
Biracial	1 (3.1%)	2 (4.1%)		
Other	1 (3.1%)	2 (4.1%)		
Year in College				
Freshman	34 (68.0%)	31 (63.3%)		
Sophomore	10 (20.0%)	8 (16.3%)	4.05	.40
Junior	3 (6.0%)	5 (10.2%)		
Senior / Senior +	3 (6.0%)	5 (10.2%)		
Psychotropic Use				
Yes	6 (12.0%)	5 (10.2%)	< 0.01	1.0
No	44 (88.0%)	44 (88.9%)		
Trait Affect				
Positive Affect	28.8 (4.9)	29.7 (4.8)	-0.98	0.33
Negative Affect	19.2 (4.8)	18.4 (4.8)	0.87	0.39
Reading Scores				
Reading Ability	3.95 (2.1)	3.5 (2.0)	1.12	.27
Word Finding	3.82 (1.8)	3.37 (1.9)	1.22	.22
Dyslexia	0.36 (0.63)	0.47 (.66)	4.20	.38
Native Language - English				
Yes	42 (84.0%)	45 (91.8%)	0.79	.38
No	8 (16.0%)	4 (8.2%)		
Baseline Characteristics				
SBP (mmHg)	113 (12.0)	113 (11.2)	-0.01	.99
DBP (mmHg)	67.9 (9.37)	67.6 (9.4)	0.17	.11
HR (bpm)	71.5 (10.5)	72.7 (12.9)	-0.48	.63
State PA (0 – 100 scale)	53.2 (12.6)	56.1 (12.2)	-1.19	.24
State NA (0 – 100 scale)	18.6 (11.7)	15.4 (13.5)	1.26	.21

Table 17. Post-task feedback questions and multiple-choice responses (Study 3).

Question	Responses
Did you believe that the interviewers were evaluating you during the task?	Yes No Unsure
Do you think that it was more difficult or stressful to do these tasks on Zoom (compared to doing them in person)?	A lot more difficult or stressful in person A little bit more difficult or stressful in person No difference A little bit more difficult or stressful on Zoom A lot more difficult or stressful on Zoom
How did you feel about having the session video recorded (You can choose more than one option) *	I did not mind being recorded I forgot I was being recorded It made me feel more anxious/nervous I really did not like being recorded I did not like that other people from the lab would be rating my performance
How easy or difficult was it for you to take your own blood pressure	Very easy Easy Neutral Difficult Very difficult
How do you think doing these tasks online might compare to doing these tasks in-person?	(Open ended response)
Any additional feedback or comments about the study?	(Open ended response)

* Only stress participants were asked this question.

Table 18 . Researcher documented issues that occurred during the remote TSST and participant responses to the feedback survey (Study 3).

Issues Documented	*N* of Reports		
	Control	Stress V1	Stress V2
Technical Issues			
Zoom session was unable to be recorded	0	1	0
Poor internet connection	2	0	0
Older version of Zoom	0	1	0
Cuff was placed on dominant arm	0	0	1
Could not print blood pressure readings	1	1	0
Non-compliance			
Roommate was present during task	6	2	1
Pet was in the room	0	1	1
Used an iPad instead of laptop or desktop computer	2	0	0
Not paying attention during videos (baseline or recovery)	1	0	0
Not sitting with feet flat on the floor	1	0	0
Unable to cover nearby windows	1	1	0
Unknown distraction (*e.g.*, suspected phone use, background	4	4	1

Participant Survey Responses	*N* (%) of Reports	
	Control	Stress
Did you believe that your performance was being evaluated?		
Yes	29 (58.0%)	38 (77.6%)
No	13 (26.0%)	5 (10.2%)
Unsure	8 (16.0 %)	6 (12.2%)
How might these tasks compare to performing them in person?		
A lot worse in person	3 (6.0%)	5 (10.2%)
A little bit worse in person	14 (28.0%)	23 (46.9%)
No difference	25 (50.0%)	7 (14.3%)
A little bit worse on Zoom	8 (16.0%)	11 (22.4%)
A lot worse on Zoom	-	3 (6.1%)
How easy or difficult was it for you to take your own blood pressure?		
Very easy	35 (70.0%)	27 (55.1%)
Easy	10 (20.0%)	17 (34.7%)
Neutral	5 (10.0%)	3 (6.1%)
Difficult	-	2 (2.0%)

Table 19. Correlations between cardiovascular measures and self-reported emotions at baseline (Study 3).

	SBP	DBP	HR	Vigor	Wellbeing	Calm	Avg PA	Anxiety	Depression	Hostility
SBP										
DBP	.54**									
HR	.11**	.38**								
Vigor	.12	-.14	-.15							
Wellbeing	.02	-.08	-.13	.63**						
Calm	-.12	-.07	.10	.32**	.58**					
Avg PA	.01	-.12	-.15	.82**	.89**	.76**				
Anxiety	-.08	.09	.11	.02	-.18	-.39**	-.21			
Depression	-.11	.00	-.05	-.12	-.25*	-.40**	-.30**	.62**		
Hostility	-.13	-.10	.02	.00	-.22*	-.37**	-.23*	.58**	.74**	
Avg NA	-.12	.01	.04	-.04	-.25*	-.45**	-.28*	.87**	.90**	.85**

Notes. * p <.05, ** p < 0.01 after Bonferroni correction; SBP = systolic blood pressure (mmHg); DBP = diastolic blood pressure (mmHg); HR = heart rate (bpm); all self-reported emotions are on a 0 (low) – 100 (high) scale.

Table 20. Means, standard deviations, and post-hoc p-values for the reactivity of positive emotions during the rTSST (Study 3)

Main Effects	Positivity			Vigor			Well-being			Calm		
	M	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*	*p*
Time												
Baseline	54.6	12.5	<.001	38.9	17.8	.28	54.7	14.3	<.001	70.3	15.2	<.001
Task	35.2	16.4	-	39.0	24.8	-	32.7	19.3	-	34.1	24.1	-
Recovery	53.7	12.8	<.001	34.0	18.1	.28	55.2	17.5	<.001	72.0	15.7	<.001
Group												
Control	49.0	15.1	.24	34.8	21.0	.04	49.3	18.6	.13	62.9	19.3	.006
Stress	46.7	18.0		39.8	19.9		45.7	21.4		54.6	30.4	

Group*Time Interactions	Positivity			Vigor			Well-being			Calm		
	Control	Stress	*p*	Control	Stress	*p*	Control	Stress	*p*	Control	Stress	*p*
Time												
Baseline												
M	53.2	56.1	.72	38.4	39.5	.99	54.7	54.7	.99	66.5	74.3	.03
SD	12.6	12.2		18.0	17.8		14.8	14.0		14.3	15.1	
Task												
M	40.6	29.7	.002	34.2	43.8	.17	38.0	27.3	.02	49.7	18.1	<.001
SD	15.0	16.2		23.7	25.3		18.3	19.0		20.1	16.2	
Recovery												
M	53.2	54.3	.99	31.9	36.2	.73	55.2	55.2	.99	72.4	71.6	.99
SD	14.1	11.5		20.7	14.8		17.3	17.9		15.4	16.2	

Note. all *p*-values reported are Bonferroni corrected. All *p*-values for the main effect of time are relative to task values. Bolded values are statistically significant.

Table 21. Means, standard deviations, and post-hoc p-values for the reactivity of negative emotions during the rTSST (Study 3)

Main Effects												
	Negativity			Anxiety			Depression			Hostility		
	M	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*	*p*
Time												
Baseline	17.0	12.7	<.001	26.5	17.5	<.001	16.1	15.8	<.001	8.4	10.8	<.001
Task	36.4	21.3	-	58.8	27.5	-	27.3	22.8	-	23.1	25.0	-
Recovery	16.3	14.6	<.001	20.2	17.5	<.001	17.2	17.2	<.001	11.5	15.3	<.001
Group												
Control	18.2	12.7	<.001	29.1	19.9	<.001	16.4	16.8	<.001	9.3	11.0	<.001
Stress	28.3	22.6		41.4	31.9		24.1	21.3		19.5	23.6	
Group*Time Interactions												
	Negativity			Anxiety			Depression			Hostility		
	Control	Stress	*p*	Control	Stress	*p*	Control	Stress	*p*	Control	Stress	*p*
Time												
Baseline			.63			.28			.99			.99
M	18.6	15.4		29.4	23.5		17.3	14.9		9.1	7.8	
SD	11.7	13.5		16.3	18.2		15.8	15.9		10.4	11.3	
Task			<.001			<.001			<.001			<.001
M	23.0	50.0		39.6	78.4		18.4	36.3		11.0	35.4	
SD	13.8	18.8		21.1	17.6		20.0	22.1		13.1	28.3	
Recovery			.08			.79			.08			.03
M	13.1	19.6		18.2	22.2		13.5	21.1		7.7	15.4	
SD	10.9	17.1		16.1	18.8		13.7	19.6		9.3	18.9	

Note. all *p*-values reported are Bonferroni corrected. All *p*-values for the main effect of time are relative to task values.

Table 22. Means, SDs, and post-hoc results for the MANOVAs for all measures of cardiovascular reactivity (Study 3)

Main Effects									
		SBP			DBP			HR	
	M	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*	*p*
Time									
Baseline	111.6	10.8	<.001	66.8	8.4	<.001	71.5	11.5	<.01
Prep	117.4	13.5	[a]	71.8	9.6	[a]	79.4	15.0	-
Speech	125.7	15.0	-	80.3	10.8	-	82.8	13.3	-
Math	121.6	13.8	-	75.5	10.2	-	78.6	13.6	-
Recovery 1	114.8	11.8	<.001	70.3	9.8	<.01	72.2	11.8	<.01
Recovery 2	112.0	11.4	<.001	68.7	9.0	<.001	71.4	11.4	<.001
Recovery 3	111.1	11.0	<.001	67.8	8.6	<.001	71.3	11.7	<.001
Recovery 4	111.8	11.8	<.001	68.8	8.6	<.001	72.2	11.6	<.01
Group									
Control	113.8	11.8	<.001	70.0	8.9	<.001	72.9	10.7	ns
Stress	118.0	14.8		72.7	11.6		77.3	15.3	

Group x Time Interaction Effects									
		SBP			DBP			HR	
	Control	Stress		Control	Stress		Control	Stress	
	M *SD*	*M* *SD*	*p*	*M* *SD*	*M* *SD*	*p*	*M* *SD*	*M* *SD*	*p*
Time									
Baseline	111.7	111.5	.99	67.0	66.5	.99	70.9	72.2	.99
	11.1	10.6		7.4	9.6		10.3	12.9	
Prep	113.3	122.3	.01	68.9	75.2	.01	74.4	85.4	.004
	10.6	15.0		7.9	10.4		11.2	16.8	
Speech	120.5	131.9	.002	77.1	84.1	.02	78.1	88.3	.002
	12.7	15.3		9.6	11.0		10.6	14.1	
Math	118.3	125.4	.13	73.3	78.0	.24	74.5	83.3	.02
	11.6	15.3		8.6	11.4		10.0	15.6	
Recovery 1	113.7	116.1	.99	69.5	71.2	.99	71.2	73.3	.99
	11.6	12.0		9.3	10.4		9.7	13.9	
Recovery 2	111.8	112.2	.99	68.3	69.2	.99	71.2	71.6	.99
	11.1	11.8		8.0	10.0		10.5	12.6	
Recovery 3	110.2	112.1	.99	67.4	68.3	.99	71.4	71.1	.99
	10.8	11.3		7.9	9.5		11.0	12.7	
Recovery 4	111.3	112.5	.99	68.4	69.2	.99	71.6	72.9	.99
	11.3	12.5		7.6	9.8		11.0	12.3	

Note. all *p*-values reported are Bonferroni corrected. Bolded values are statistically significant. ns indicates that the main effect was not statistically significant so no post-hoc analyses were warranted. *p*-values for the main effect of time are relative to task values (prep, speech, and math). [a] *p*-values are relative to speech and math only as prep demonstrated a different pattern of results.

Table 23. Intra-class correlations for all measures of reactivity and recovery (Study 3).

	Systolic BP			*Diastolic BP*			*Heart Rate*		
	ICC	95% CI	*p*	ICC	95% CI	*p*	ICC	95% CI	*p*
Reactivity									
Preparation									
Change score	-.27	[-.71, .26]	.84	.30	[-.20, .67]	.12	.36	[-.14, .71]	.07
Percent	.32	[-.11, .67]	.07	.48	[-.01, 78]	.03	.27	[-.26, .66]	.15
AUCg	.77	[.49, .91]	<.001	.83	[.59, .94]	<.001	.88	[.70, .96]	<.001
AUCi	.76	[.45, .90]	<.001	.85	[.63, .94]	<.001	.88	[.71, .96]	<.001
Speech Task									
Change score	.32	[-.11, .67]	.07	.48	[-.01, .78]	.03	.27	[-.26, .66]	.15
Percent	.33	[-.09, .68]	.06	.48	[-.01, .78]	.03	.50	[.02, .78]	.02
AUCg	.70	[.33, .88]	<.001	.71	[.36, .88]	<.001	.73	[.39, .89]	<.001
AUCi	.68	[.31, .87]	.001	.70	[.35, .88]	<.001	.71	[.36, 89]	<.001
Math Task									
Change score	-.08	[-.57, .42]	.62	.13	[-.39, .58]	.31	.15	[-.33, .57]	.28
Percent	-.14	[-.62, .37]	.71	.05	[-.47, .52]	.43	.09	[-.40, .53]	.37
AUCg	.58	[.15, .82]	<.001	.70	[.35, .88]	<.001	.92	[.80, .97]	<.001
AUCi	.56	[.12, .82]	.008	.69	[.34, .88]	<.001	.92	[.80, 97]	<.001
Average									
Change score	.12	[-.36, .55]	.55	.39	[-.12, .73]	.06	.59	[.19, .83]	.004
Percent	.12	[-.35, .55]	.32	.31	[-.22, .68]	.12	.47	[.02, .77]	.02
AUCg	.72	[.36, .89]	<.001	.85	[.63, .94]	<.001	.88	[.71, .96]	<.001
AUCi	.68	[.29, .87]	.001	.84	[.61, .94]	<.001	.89	[.72, .96]	<.001
Recovery									
CS- baseline	.10	[-.31, .48]	.32	-.01	[-.40, .38]	.52	.32	[-.10, .63]	.06
CS- task	.58	[.23, .79]	.001	.24	[-.19, .59]	.13	.53	[.16, .76]	.003
PC- baseline	.07	[-.33, .45]	.37	-.11	[-.49, .30]	.70	.24	[-.18, .59]	.13
PC- task	.52	[.16, .76]	.004	.21	[-.22, .56]	.17	.50	[.14, .75]	.005
AUC- ground	.86	[.67, .94]	<.001	.89	[.74, .96]	<.001	.91	[.79, .97]	<.001
AUC- increase	.87	[.70, .95]	<.001	.89	[.74, .96]	<.001	.91	[.77, .96]	<.001

Note. All ICCs were calculated as 2-way mixed effects models with absolute agreement. Bolded items meet our predictions of ICC ≧ .60. Abbreviations: CS = change score; PC = percent change; AUC = area under the curve.

Table 24. Correlations between study visits using various methods of measuring blood pressure recovery (Study 3).

		Visit 1						Visit 2					
		Diastolic Blood Pressure Recovery											
		1	2	3	4	5	6	7	8	9	10	11	12
Visit 1	1. CS-B		-.12	.99	-.09	.02	.03	.34	.06	.31	.03	.13	.17
	2. CS-T	-.33		-.10	.99	.11	-.02	-.41	.53	-.45	.51	.11	.07
	3. PC-B	.99	-.32		-.06	-.02	.00	.30	.10	.26	.07	.12	.16
	4. PC-T	-.36	.95	-.34		-.01	-.13	-.40	.55	-.43	.55	.03	-.02
	5. AUCg	.02	.47	-.02	.20		.99	.19	-.19	.12	-.37	.89	.89
	6. AUCi	.05	.42	.00	.14	.99		.24	-.22	.17	-.39	.89	.89
Visit 2	7. CS-B	.27	-.78	.23	-.80	-.17	-.11		-.51	.99	-.55	.27	.33
	8. CS-T	-.42	.71	-.40	.72	.15	.12	-.79		-.51	.98	-.10	-.21
	9. PC-B	.25	-.74	.22	-.79	-.12	-.07	.99	-.78		-.54	.20	.25
	10. PC-T	-.39	.60	-.36	.68	-.03	-.07	-.76	.97	-.77		-.30	-.39
	11. AUCg	-.05	.37	-.10	.11	.86	.87	-.02	.11	.02	-.10		.99
	12. AUCi	.01	.32	-.04	.05	.86	.87	.04	.01	.09	-.20	.99	
		Systolic Blood Pressure Recovery											

Note. The bottom half of the correlation matrix are the correlations for systolic blood pressure whereas the top half are the correlations for diastolic blood pressure. Bolded values are statistically significant at $p < .05$ after Bonferroni correction. CS-B: change score from baseline; CS-T: change score from task; PC-B: percent change from baseline; PC-T: percent change from task; AUCg: area under the curve with respect to ground; AUCi: area under the curve with respect to increase; For CS-T and PC-T measures, smaller numbers reflect poorer recovery. For all other measures, smaller numbers represent better recovery.

Table 25. Correlations between study visits using various methods of measuring heart rate recovery (Study 3).

		Visit 1						Visit 2				
		1	2	3	4	5	6	7	8	9	10	11
Visit 1	1. CS-B											
	2. CS-T	-.28										
	3. PC-B	.98	-.25									
	4. PC-T	-.40	.92	-.38								
	5.	.62	-.13	.56	-.45†							
	6. AUCi	.61	-.16	.55	-.49	.99						
Visit 2	7. CS-B	.52	-.03	.51	-.14	.36	.37					
	8. CS-T	-.02	.69	-.07	.65	.12	.07	.10				
	9. PC-B	.50	-.02	.51	-.12	.31	.32	.99	.06			
	10. PC-	-.26	.68	-.30	.74	-.21	-.25	-.06	.93	-.08		
	11.	.71	.03	.63	-.24	.91	.89	.42	.26	.36	-.08	
	12.	.71	.00	.64	-.28	.92	.90	.40	.20	.35	-.13	.99

Note. Bolded values are statistically significant at $p < .05$ and † $p =. 05$ after Bonferroni correction. CS-B: change score from baseline; CS-T: change score from task; PC-B: percent change from baseline; PC-T: percent change from task; AUCg: area under the curve with respect to ground; AUCi: area under the curve with respect to increase; For CS-T and PC-T measures, smaller numbers reflect poorer recovery. For all other measures, smaller numbers represent better (more complete) recovery.

Table 26. Mean and standard deviation of self-reported task engagement by group (Study 3).

	Control	Stress	Difference	
	M (*SD*)	*M* (*SD*)	*t-statistic*	*p-value*
Fatigue	49.8 (24.8)	62.6 (24.2)	-2.59	.01
Motivation	59.8 (24.4)	55.8 (26.5)	0.78	.44
Task Importance	58.8 (25.1)	61.9 (23.4)	-0.63	.53
Task Difficulty	18.9 (15.8)	72.9 (19.1)	-15.30	<.001
Task Effort	49.2 (20.5)	71.5 (15.4)	-6.12	<.001
Average Effort	47.3 (14.1)	64.9 (12.5)	-6.58	<.001

Table 27. Pearson's correlations between trait measures of positive and negative affect and cardiovascular stress recovery (Study 3)

	SBP rec	DBP rec	HR rec	Trait PA	Trait NA
	p – values (Bonferroni correction)				
SBP recovery		<.001	.27	.99	.99
DBP recovery	.58*		.99	.99	.82
HR recovery	-.33	.14		.99	.99
Trait PA	.02	-.22	-.16		.13
Trait NA	.04	.26	.02	-.38	
	Pearson's correlations (*r*)				

Note. Correlation coefficients are presented on the left of the diagonal; *p*-values are presented on the right of the diagonal. All recovery measures are calculated by area under the curve with respect to increase. * $p < .05$.

Table 28. Pearson's correlations between emotional and cardiovascular stress reactivity (Study 3)

	SBP	DBP	HR	PA	NA
	p – values (Bonferroni correction)				
SBP reactivity		<.001	.99	.99	.99
DBP reactivity	.70*		.99	.99	.99
HR reactivity	.03	.18		.99	.99
PA reactivity	-.03	-.24	.04		.01
NA reactivity	-.03	.12	-.03	-.46*	
	Pearson's correlations (*r*)				

Note. Correlation coefficients are presented on the left of the diagonal; *p*-values are presented on the right of the diagonal. All reactivity measures are calculated by area under the curve with respect to increase. * $p < .05$

7.0 Figures

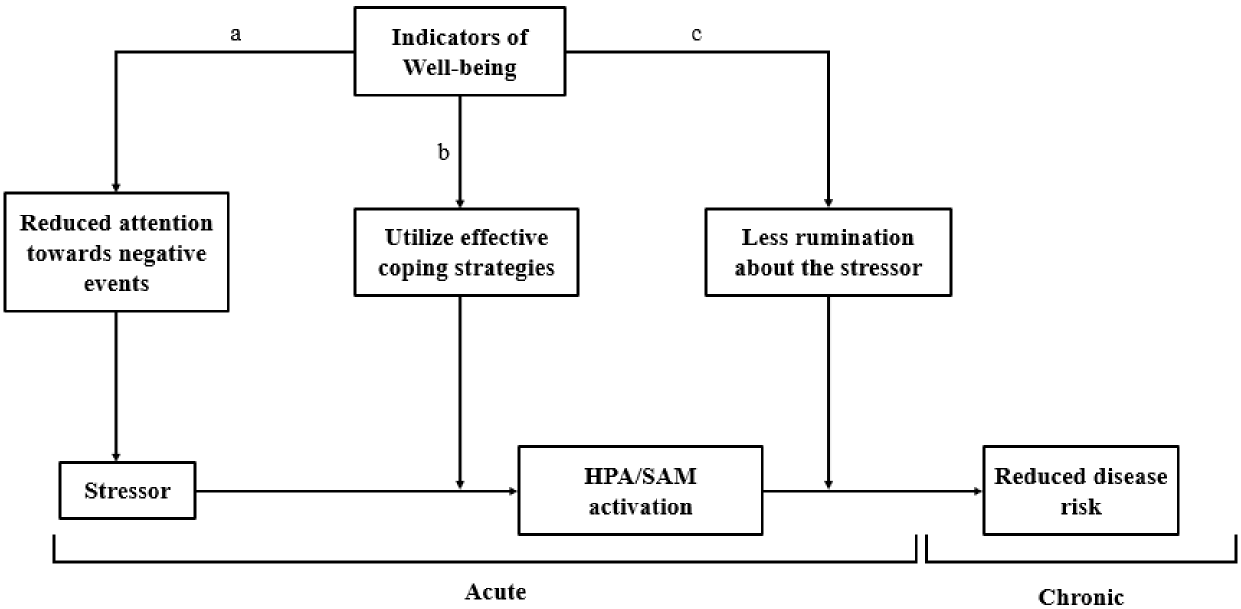

Figure 1. Conceptual model depicting potential mechanisms relating indicators of well-being to stress-related physiology and possible future disease risk.

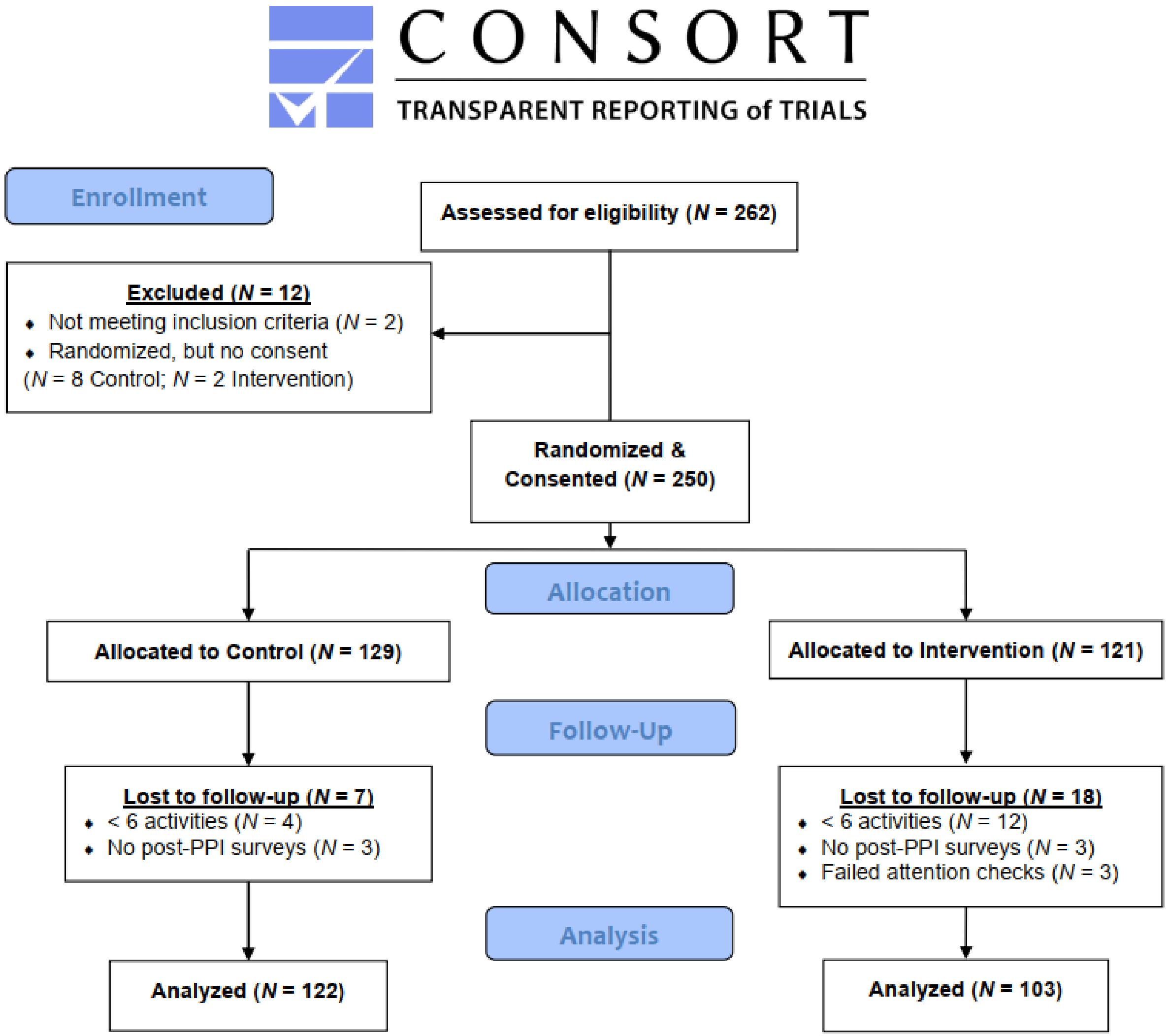

Figure 2. Study 1: CONSORT flow chart describing the enrollment, recruitment, and retention of study participants for the positive psychological intervention.

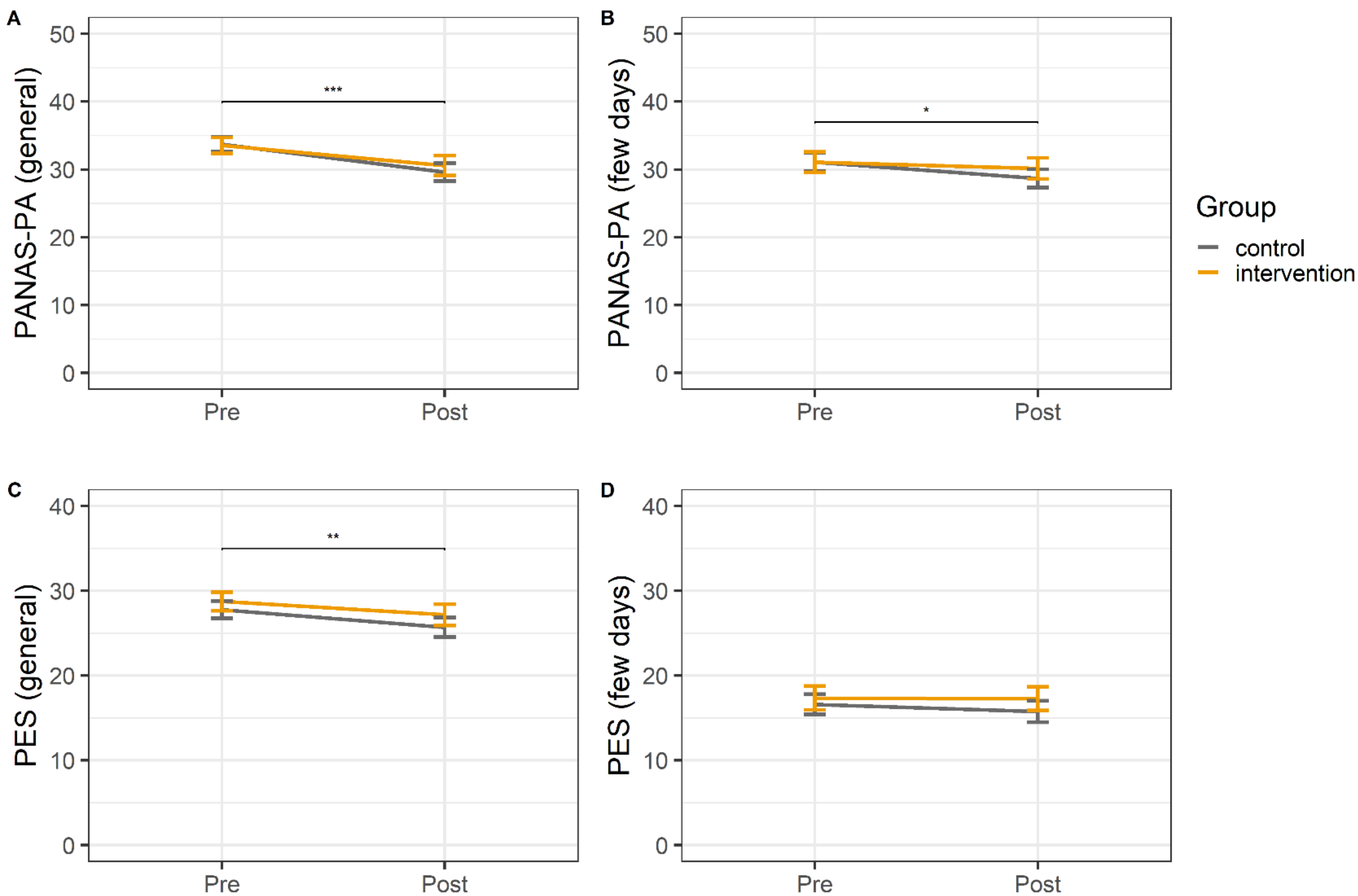

Figure 3. Study 1: Changes in self-reported positive affect from pre- to post-intervention in the control and intervention conditions using (A) PANAS-PA (in general), (B) PANAS-PA (last few days), (C) Positive Emotional Style (in general) and (D) Positive Emotional Style (last few days).

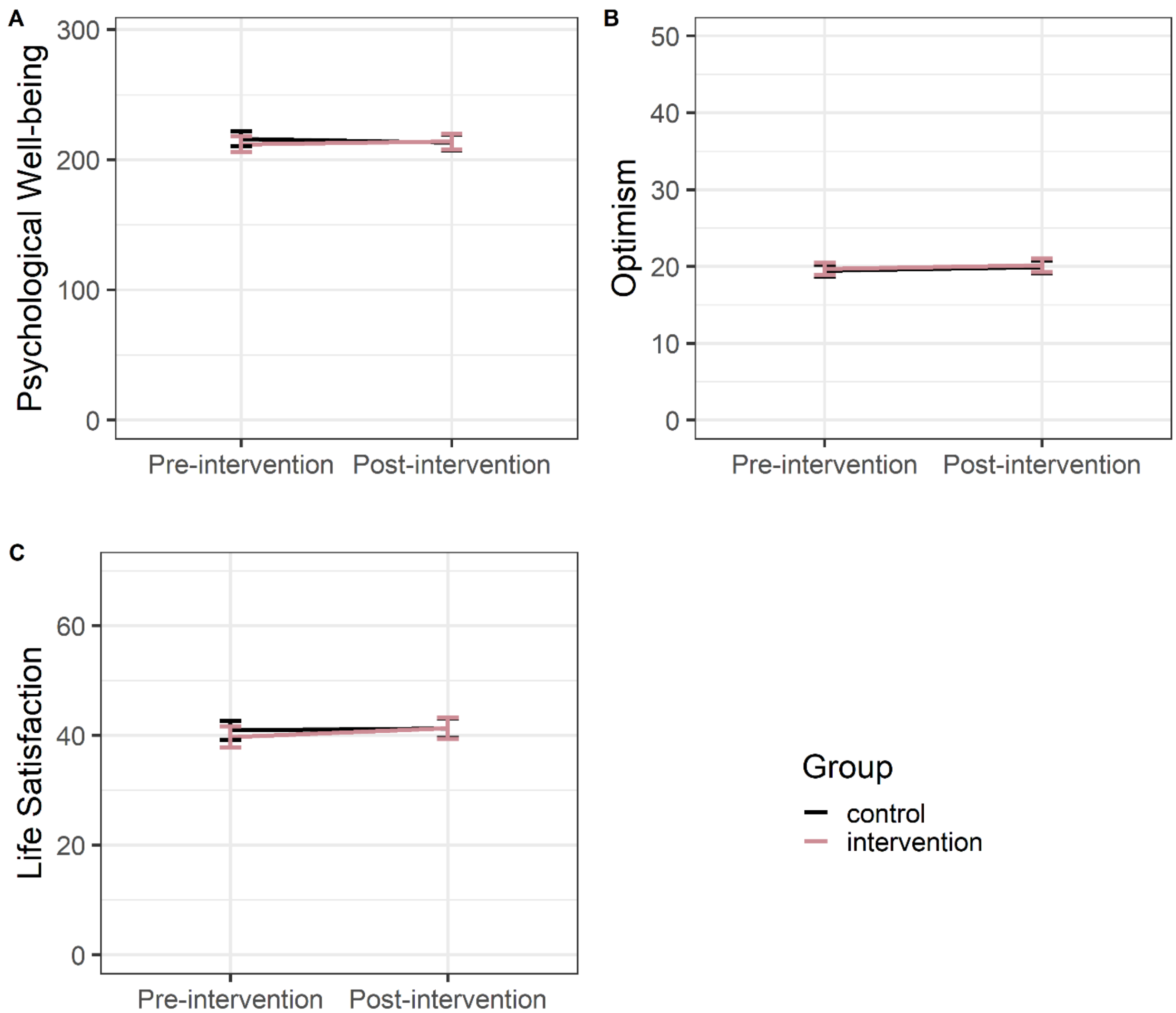

Figure 4. Study 1: Changes in self-reported well-being from pre- to post-intervention in the control and intervention conditions using the (A) Psychological Well-being Scale, (B) Life Orientation Test- Revised, and (C) PROMIS-General Life Satisfaction scales.

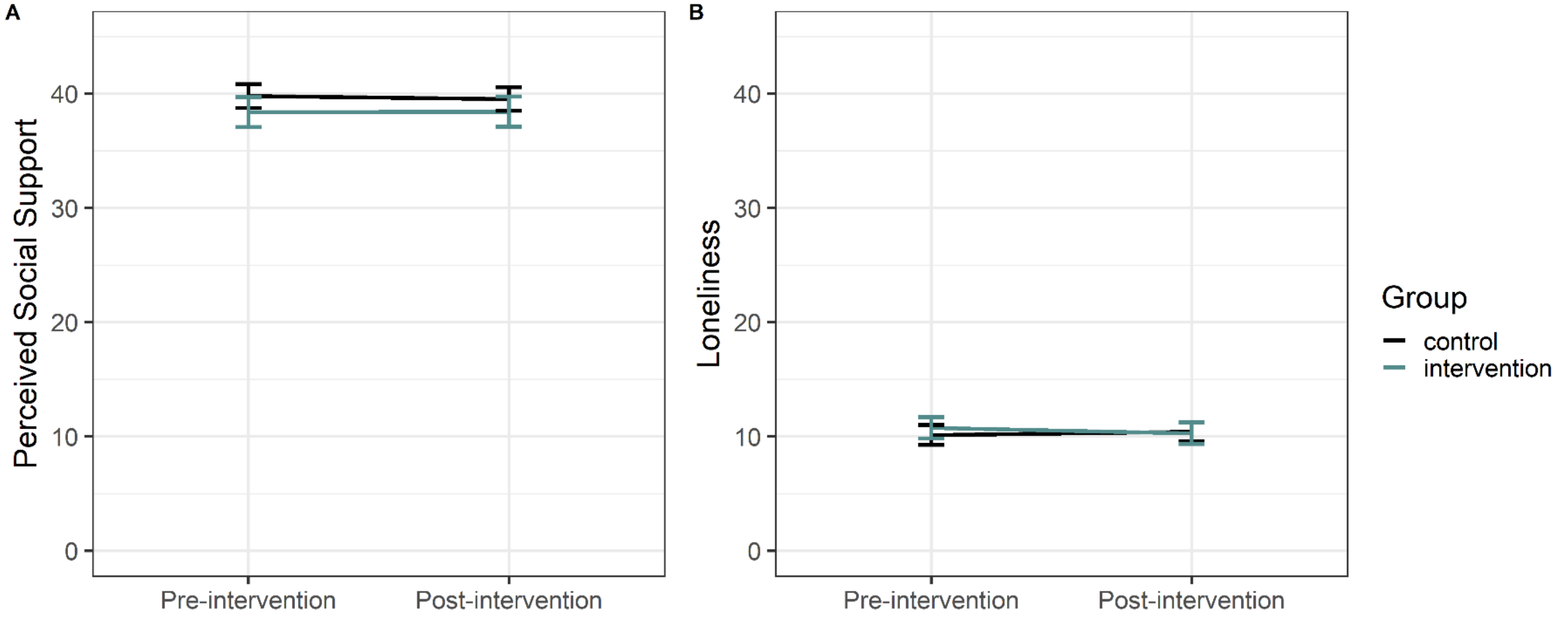

Figure 5. Study 1: Changes in self-reported social factors from pre- to post-intervention in the control and intervention conditions using the (A) Interpersonal Support Evaluation List and (B) UCLA Loneliness Scale.

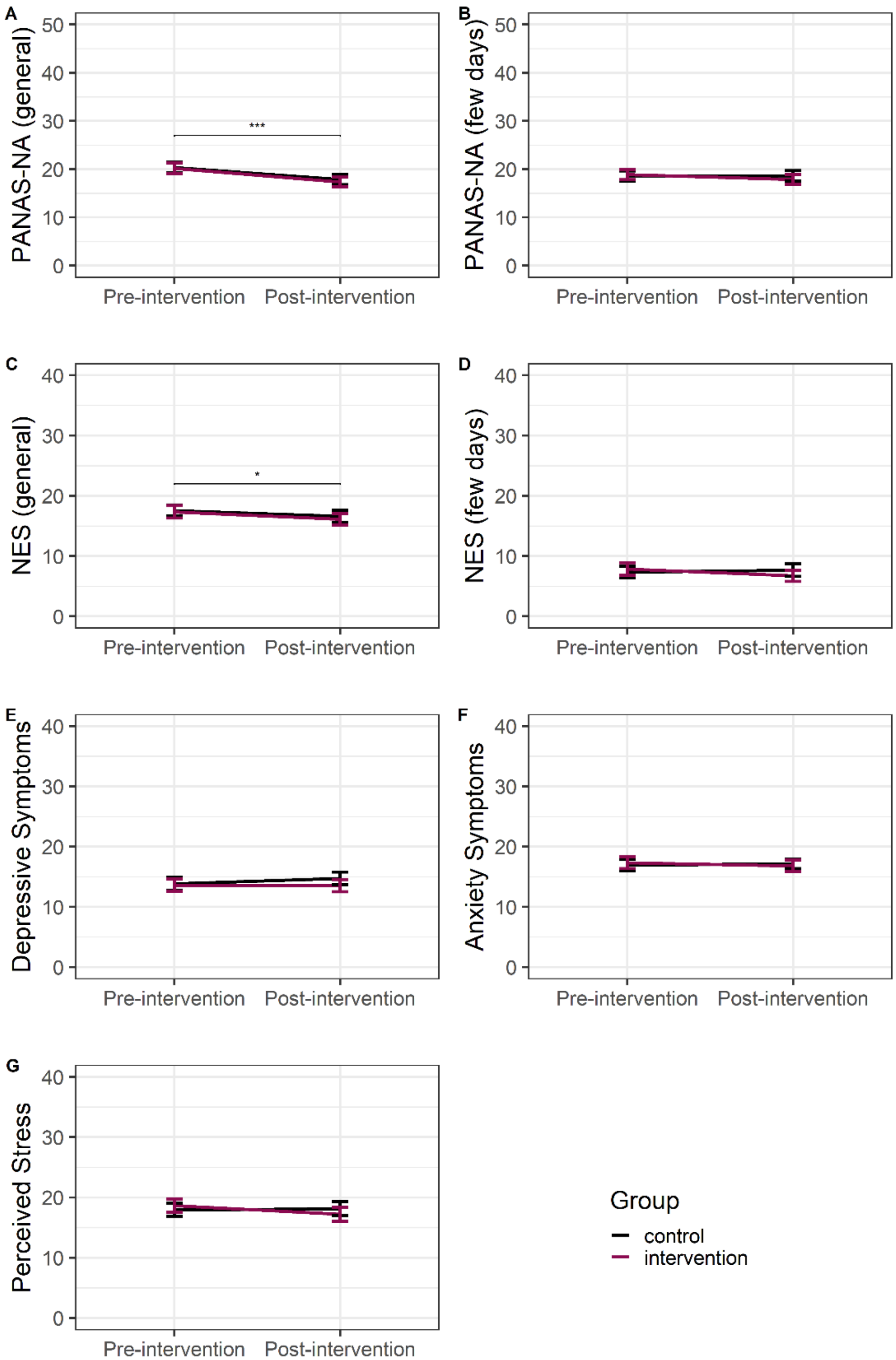

Figure 6. Study 1: Changes in self-reported negative affect and related constructs from pre- to post-intervention in the control and intervention conditions using (A) PANAS-NA (in general), (B) PANAS-NA (last few days), (C) Negative Emotional Style (in general), (D) Negative Emotional Style (last few days), (E) PROMIS-Depression-Short Form, (F) PROMIS-Anxiety-Short Form, and (G) Perceived Stress Scale.

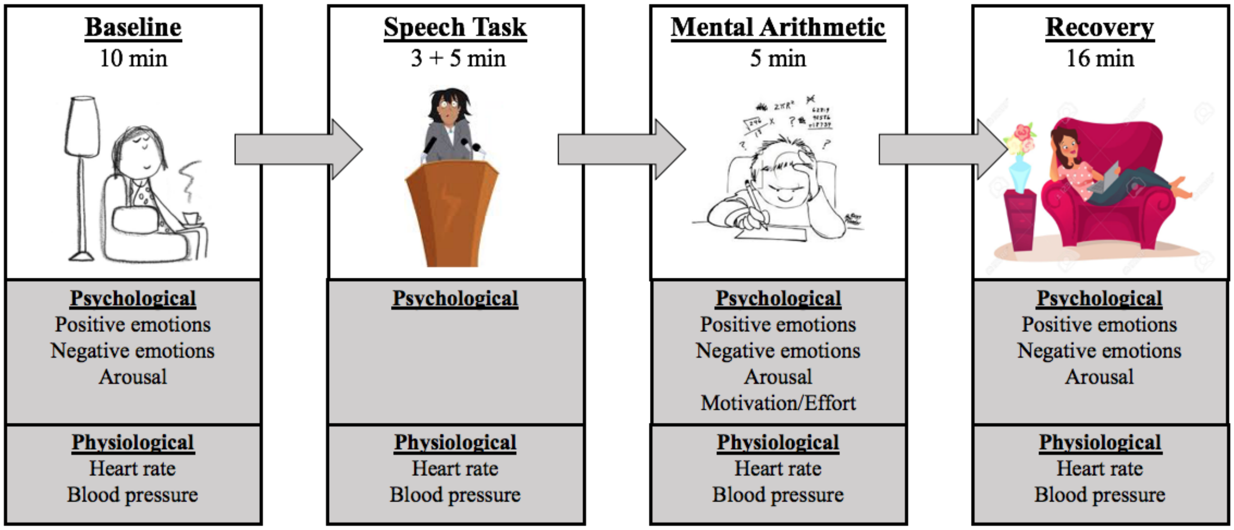

Figure 7. Studies 2 & 3: Outline of laboratory visit, including psychological and physiological variables collected at each time point.

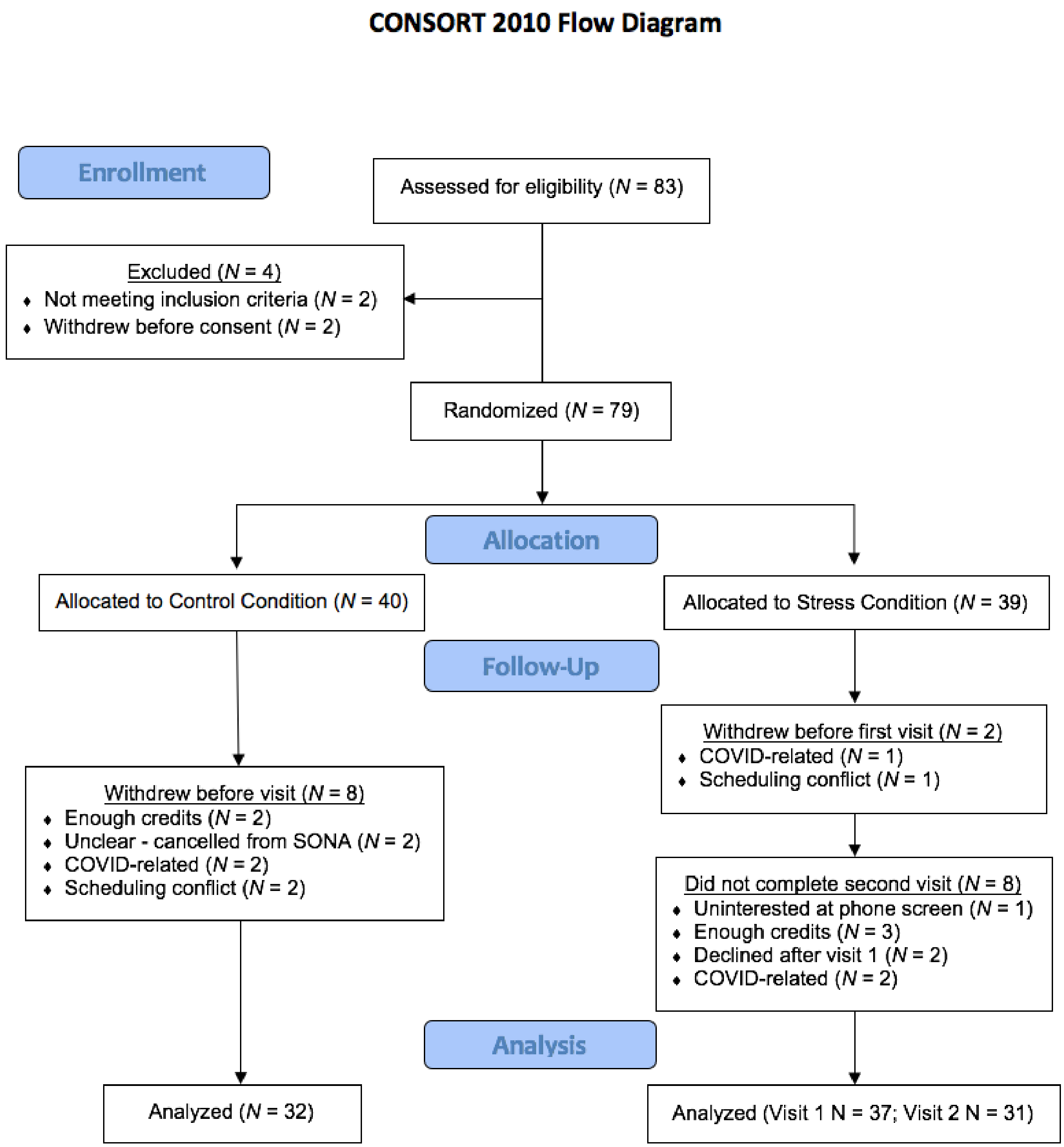

Figure 8. Study 2: CONSORT flow chart describing the enrollment, recruitment, and retention of study participants for the remote TSST.

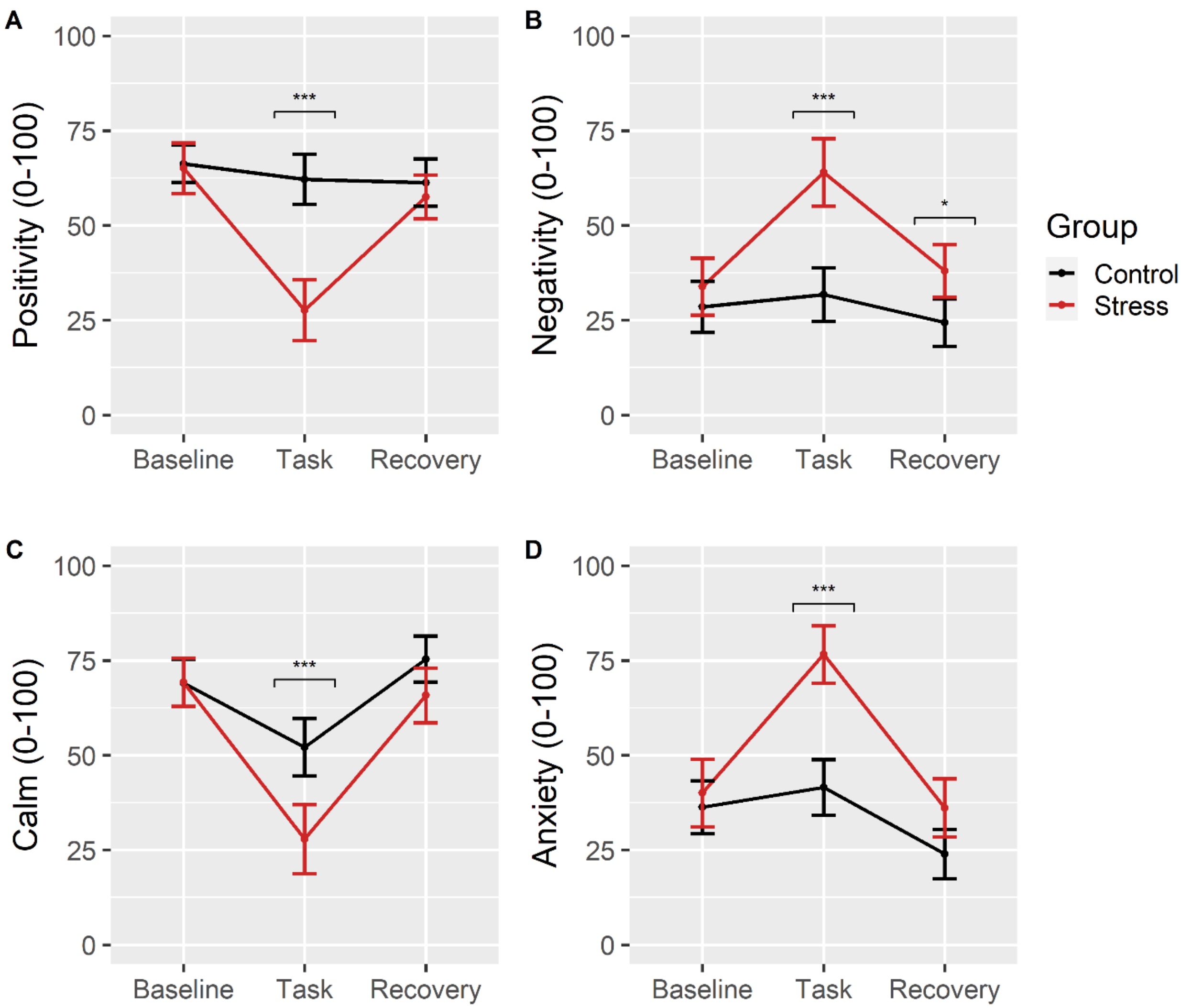

Figure 9. Study 2: Changes in emotional variables during the remote TSST including (A) positivity, (B) negativity, (C) calm, and (D) anxiety. All emotional variables were collected on a scale from 0 (low) to 100 (high). Error bars represent 95% confidence intervals.

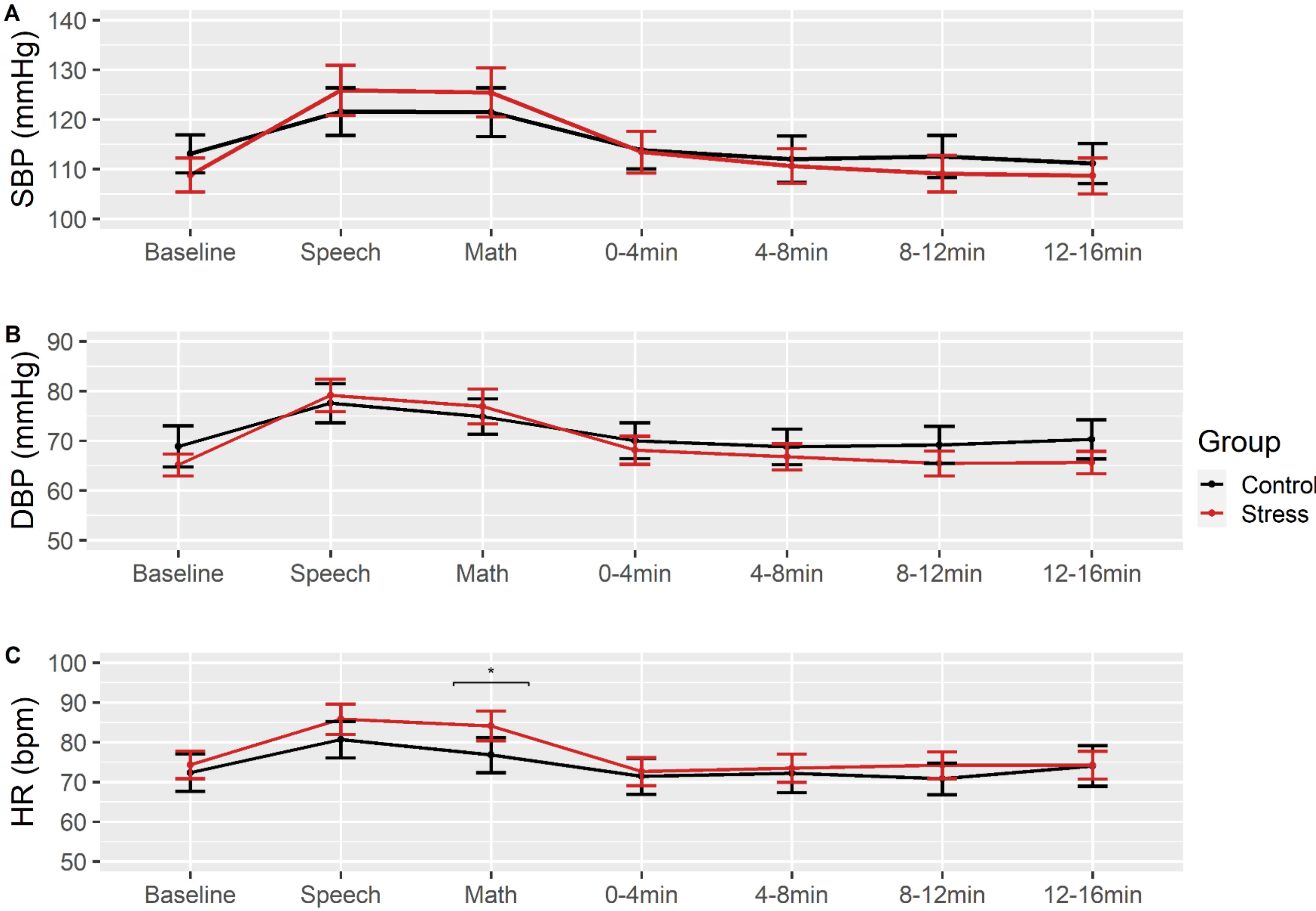

Figure 10. Study 2: Physiological reactivity and recovery by condition. Error bars are 95% confidence intervals.

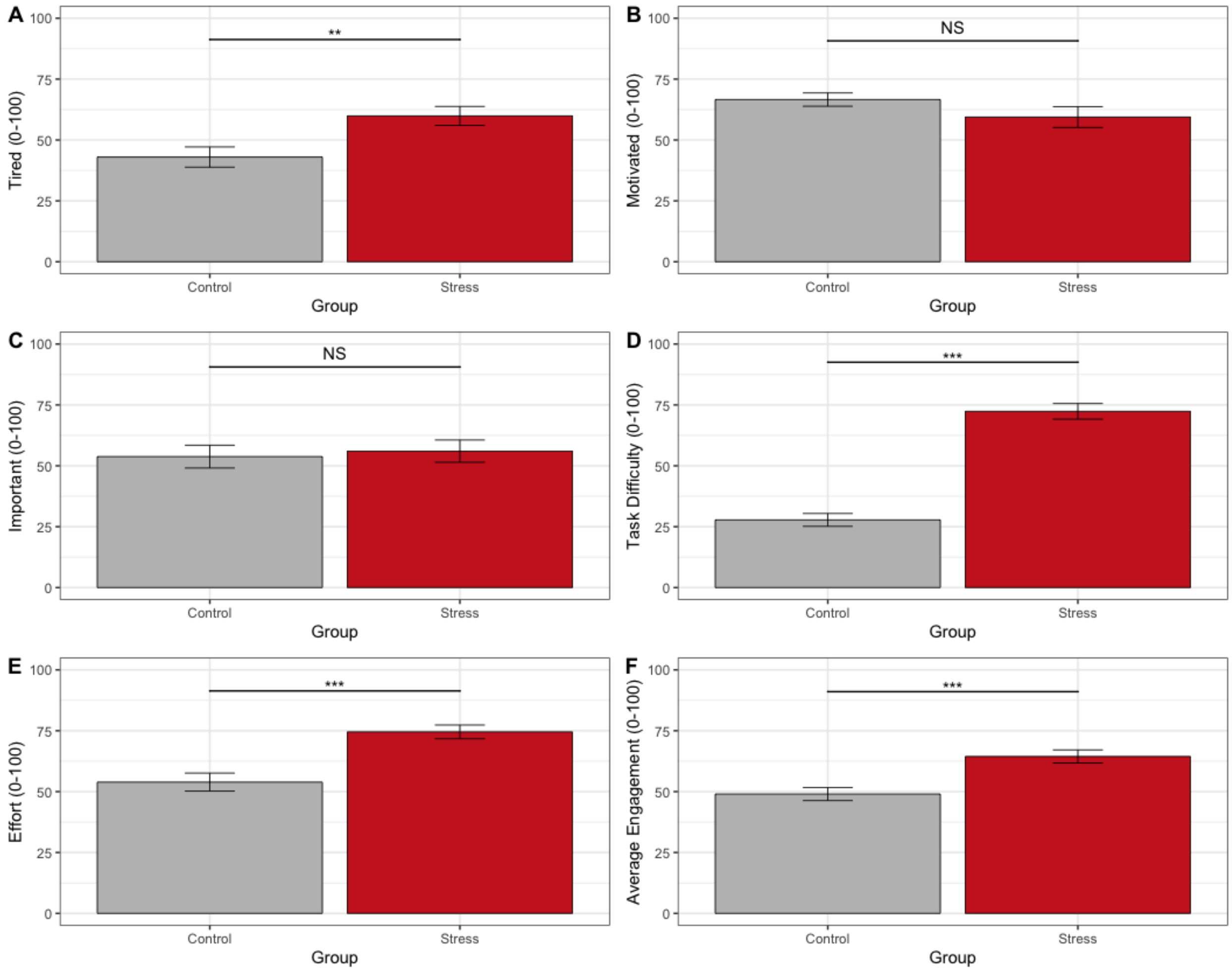

Figure 11. Study 2: Measures of motivated engagement by condition including self-reported (A) tiredness after the task, (B) motivation to perform well on the task, (C) importance of performing well on the task, (D) task difficulty, (E) Effort exerted during the task and (F) average engagement across the five variables. All variables are on a 0 (low) to 100 (high) scale. Error bars indicate standard error.

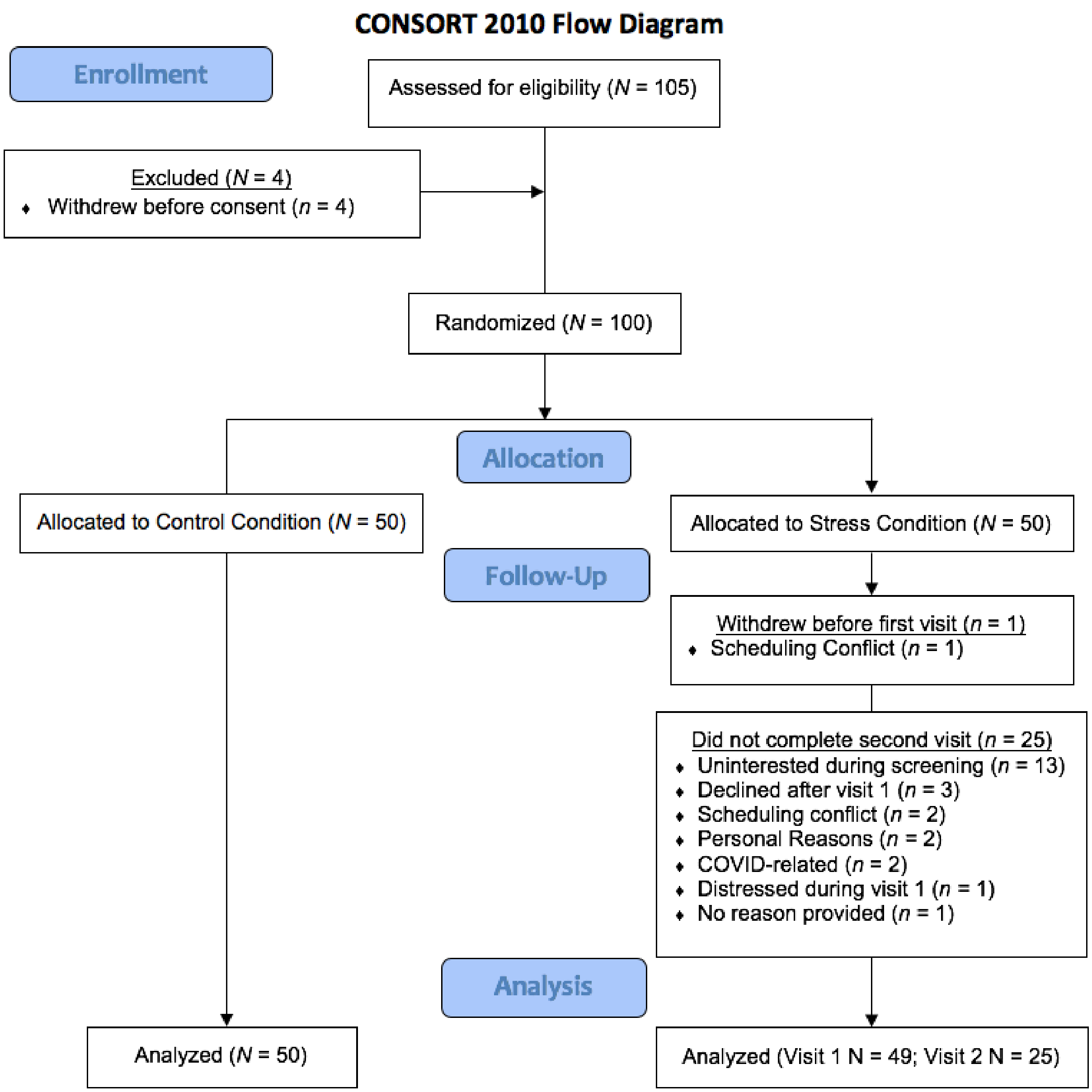

Figure 12. Study 3: CONSORT flow chart describing the enrollment, recruitment, and retention of study participants for the remote TSST (Study 3).

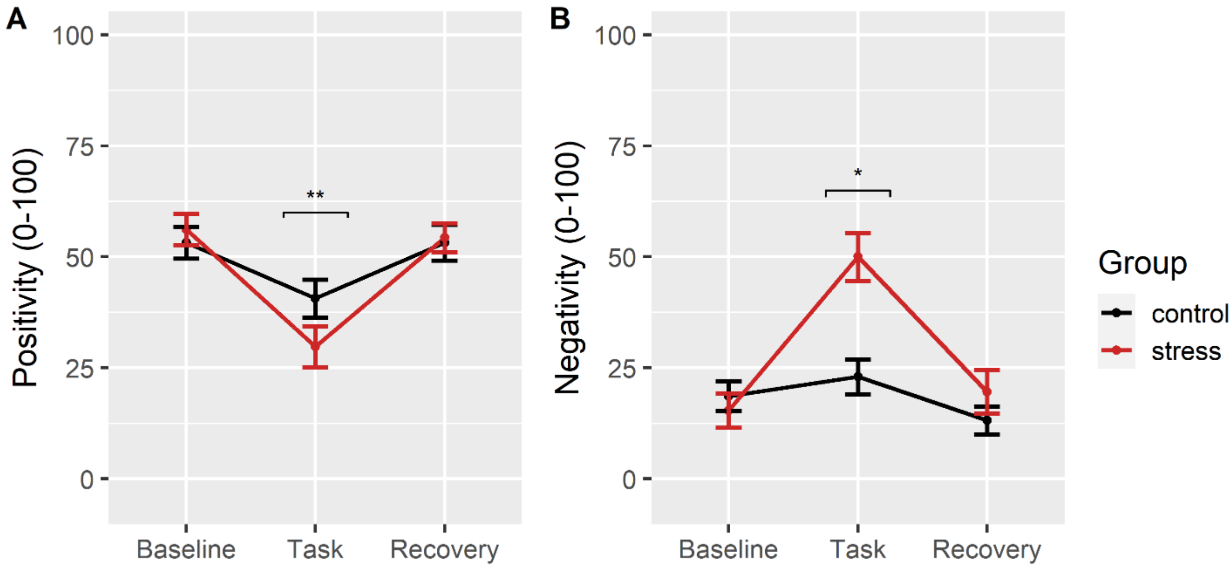

Figure 13. Study 3: Changes in average positive (A) and negative (B) emotions during the remote rTSST (Study 3). All emotional variables were collected on a scale from 0 (low) to 100 (high). Error bars indicate 95% confidence intervals.

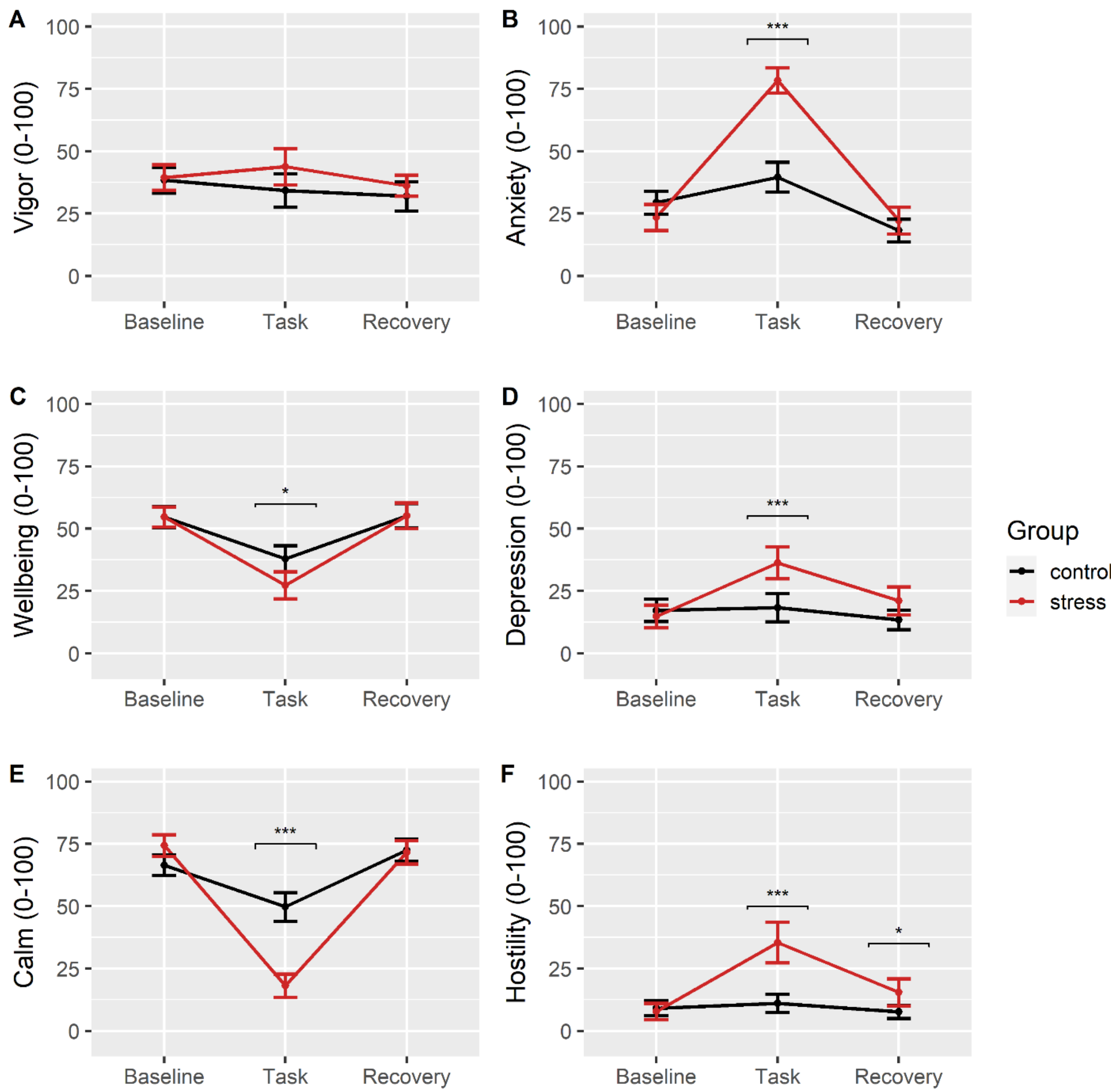

Figure 14. Study 3: Changes in subtypes of positive and negative emotions during the remote rTSST (Study 3), including (A) vigor, (B) anxiety, (C) well-being, (D) depression, (E) calm, and (F) hostility. All emotional variables were collected on a scale from 0 (low) to 100 (high). Error bars indicate 95% confidence intervals.

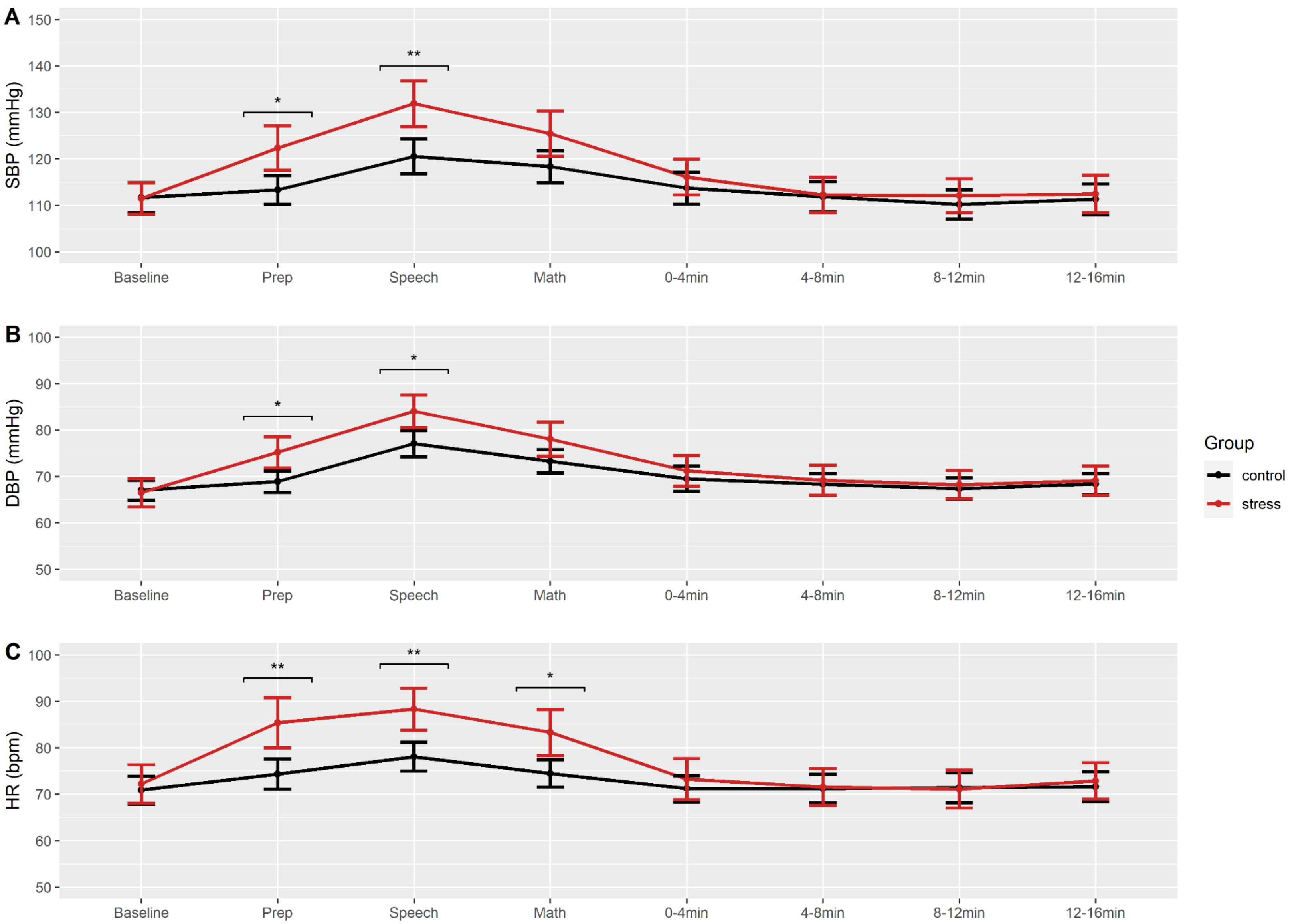

Figure 15. Study 3: Physiological reactivity and recovery by condition. Error bars indicate 95% confidence intervals.

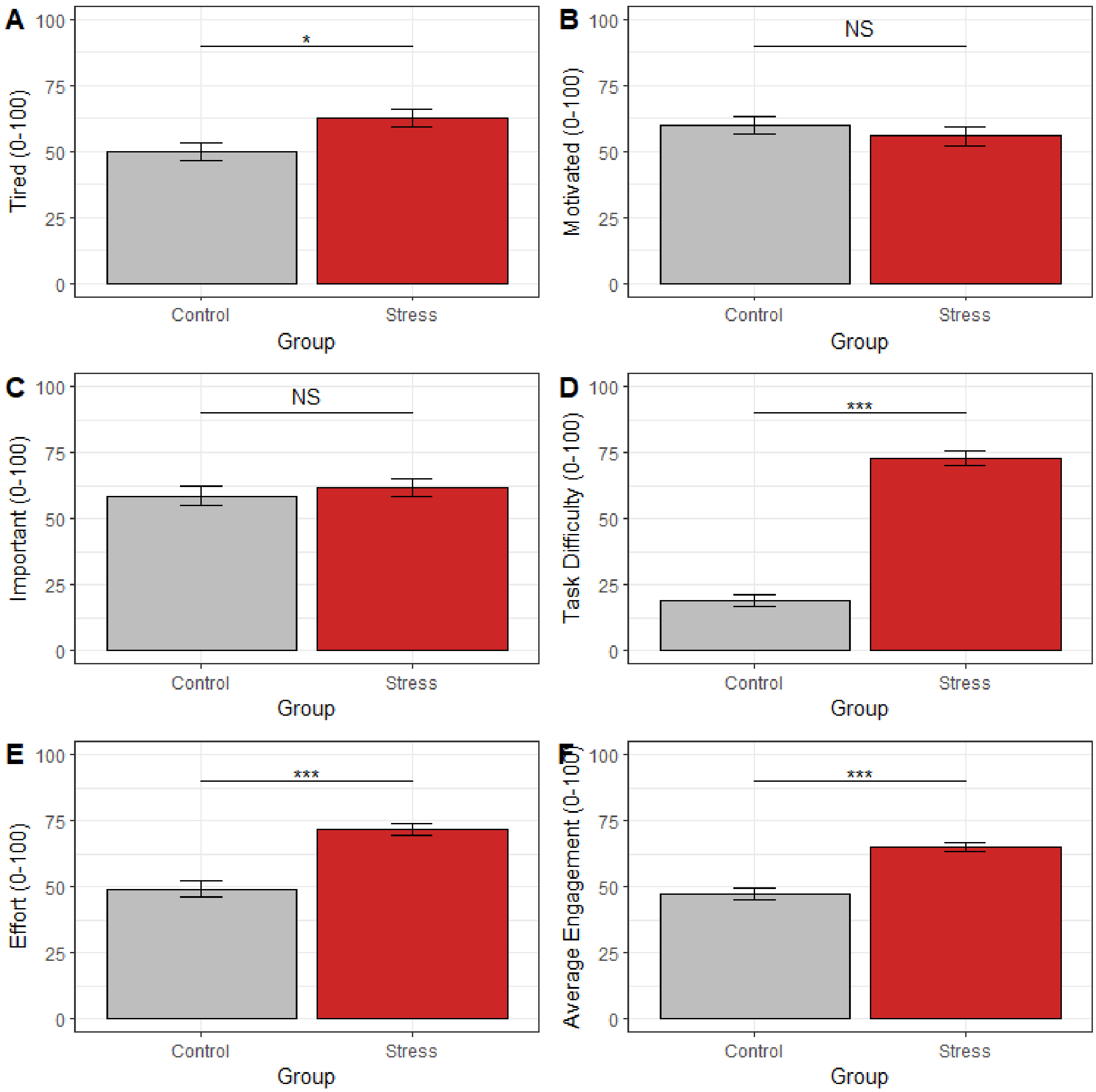

Figure 16. Study 3: Measures of motivated engagement by condition including self-reported (A) tiredness after the task, (B) motivation to perform well on the task, (C) importance of performing well on the task, (D) task difficulty, (E) Effort exerted during the task and (F) average engagement across the five variables. All variables are on a 0 (low) to 100 (high) scale. Error bars represent the standard error. * *p* < .05; * *p* <.001**

Appendix A Positive Psychological Intervention Activities

Appendix A.1 Active Control Condition

Appendix A.1.1 Daily Instructions

Activity: Take a moment and think through your day from start to finish. Think about your day in terms of the actions or behaviors that you performed.

Writing Prompt: Document your events for the day starting from the moment you woke up. You are encouraged to keep your statements brief and to write in bullet points and incomplete sentences. Please do not provide any information about your reactions or emotional responses to those events, but instead focus on the events themselves. For example, "Woke up and brushed my teeth; ate a granola bar and an apple for breakfast; walked to class; listened to the instructor." Notice that these items all include action words and stick to the events of the day without describing how you felt during or after the events. Try to write down as many events about the day as you can remember, following this format.

Appendix A.2 Positive Psychological Intervention

Appendix A.2.1 Signature Strengths

Activity: Signature strengths refers to those character strengths that are most essential to who we are. Because of this, everyone has different set of signature strengths. Look at the list below and find the strengths that resonate with what you find that you are naturally good at – those are your signature strengths. For this activity, you will pick one of your signature strengths and use it in a new and different way today. You can apply the strength in a new environment or when interacting with a 'new' person. It is up to you how you want to apply this strength. Try to apply this strength, regardless of whether you feel like you are already using the strength frequently or not. Once you select which strength you would like to use today, you will see a list of suggested activities for the signature strength that you selected. You do not have to use these activities. You can design whatever you think will work for you as long as it allows you to use one of your signature strengths.

[see document ‘Strength Suggestions’ for the various options that participants will read.]

Writing prompt: Take a moment to reflect on how you used your signature strength today. Write about which strength you used and how you used this strength in a new way. What was that experience like for you?

Adapted from: Proyer, R. T., Gander, F., Wellenzohn, S., & Ruch, W. (2015). Strengths-based positive psychology interventions: A randomized placebo-controlled online trial on long-term effects for a signature strengths-vs. a lesser strengths-intervention. *Frontiers in psychology*, *6*, 456.

Appendix A.2.2 Three Good Things

Activity: Today you will try to cultivate a sense of gratitude. ‘‘Cultivate a sense of gratitude’’ means that you make an effort to think about the many things in your life, both large and small, that you have to be grateful about. These might include particular supportive relationships, sacrifices or contributions that others have made for you, facts about your life such as your advantages and opportunities, or even gratitude for life itself, and the world that we live in. In all of these cases you are identifying previously unappreciated aspects of your life, for which you can be thankful. You may not have thought about yourself in this way before but would like to think in this way today.

Writing prompt: Think back on everything that happened today. Write about three good things, both large and small, that you have to be grateful for today. Outline the reasons why you are grateful for these things in as much detail as you can.

Adapted from: Sheldon, K. M., & Lyubomirsky, S. (2006). How to increase and sustain positive emotion: The effects of expressing gratitude and visualizing best possible selves. *The journal of positive psychology*, *1*(2), 73-82.

Appendix A.2.3 Acts of Kindness

Activity: Perform one intentional act of kindness for someone today. An act of kindness is a behavior that benefit other people or make others happy, that typically occur at some cost to yourself; for example, donating blood or helping a friend with their homework. This activity should be in additional to things that you are already doing. You may choose to perform this act of kindness to someone you know well or a complete stranger.

Writing prompt: Describe the act of kindness that you did for someone else today. How did it make you feel to perform this act of kindness? How do you think that your act of kindness might have influenced the other person? How might your act of kindness make the other person feel?

Adapted from: Lyubomirsky, S., Sheldon, K. M., & Schkade, D. (2005). Pursuing happiness: The architecture of sustainable change. *Review of general psychology*, *9*(2), 111-131.

Appendix A.2.4 Best Future Self

Activity: *Today you are going to think of your best possible self. Your best possible self means imagining yourself in a future in which everything has turned out as good as possible. You have worked hard, and you have managed to realize all your life goals. You can envision it as satisfying all your life dreams and development of all your best possible potentials. In a moment, you are going to think of the best possible ways in which your life could develop on three domains (Personal, Relational, and Professional), with the goal to direct the decisions you make in the present. You have probably never thought about yourself in this way before. In order to determine and guide constructing your best possible self, for the next few minutes, you are going to think of and write down your goals, skills, and desires that you would like to achieve in the far future for each of the three domains, and finally merge these into a personal story like a diary. During this process, think of realistic skills and manageable goals/wishes that you would like to possess or attain in the future.*

*Personal domain: Think of goals you would like to attain on the personal level (*e.g. *physical and psychological skills and developments)*.

*Professional domain: Think of goals you would like to attain on the professional/work-related level (*e.g. *position, accomplishments, level of expertise, but also occupation and skills, etc.)*.

*Relational domain: Think of goals you would like to attain on the relational level (*e.g. *relations and contacts with loved ones, friends, colleagues, but also joint activities etc. in your social life)*.

Writing prompt: *Now we would like to ask you to write down in as much detail as possible your ideal future. You can use the goals you have just constructed as a guide, while describing your thoughts, feelings, and perceptions, while making a personal story of it*.

Adapted from: Meevissen, Y. M., Peters, M. L., & Alberts, H. J. (2011). Become more optimistic by imagining a best possible self: Effects of a two week intervention. Journal of behavior therapy and experimental psychiatry, 42(3), 371-378.)

Appendix A.2.5 Gratitude Letter

Activity: In this exercise, you will write a letter to someone that has touched your life in a meaningful way. This can include family members, friends, teachers, or someone else who has impacted your life. Try to pick someone who is still alive and who you could meet with today either virtually or in-person.

- First, you will be asked to write a letter to one of these people, guided by the following steps:
- Write as though you are addressing this person directly ("Dear ________")
- Don't worry about perfect grammar or spelling
- Describe in specific terms what this person did, why you are grateful to this person, and how this person's behavior affected your life. Try to be as concrete as possible.
- Describe what you are doing in your life now and how you often remember their efforts
- Try to keep the letter to roughly one page (~ 300 words or less)

Next, you will be asked to deliver/convey your letter to the person

- Plan a zoom chat, phone date, or in-person visit (if possible and safe) with the recipient. Let that person know that you would like to see him or her and that you have something special to share – but do not tell them the exact purpose.
- When you meet, let the person know that you are grateful to them and would like to read a letter expressing your gratitude. Ask that they refrain from interrupting until you're done.
- Take your time reading the letter. While you read, pay attention to their reaction as well as your own
- After you have read the letter, be receptive to their reaction and discuss your feelings together
- Remember to give a copy of the letter to the person

Writing prompt: When you are finished with the gratitude letter, please copy and paste it in the box below. If you feel like some of the details of your letter are too personal, you can modify or redact portions of it in the version you turn in. You may also include a brief description of what it was like for you to share your letter with them.

Adapted from: Kumar, A., & Epley, N. (2018). Undervaluing gratitude: Expressers misunderstand the consequences of showing appreciation. *Psychological science*, *29*(9), 1423-1435; Lyubomirsky, S., Dickerhoof, R., Boehm, J. K., & Sheldon, K. M. (2011). Becoming happier takes both a will and a proper way: an experimental longitudinal intervention to boost well-being. *Emotion*, *11*(2), 391.

Appendix A.2.6 Savoring with Mindful Photography

Activity: Throughout the course of the day, you will take photographs of your everyday life. As you do the exercise, think about the things in your life that bring you happiness or joy. What brings you positive feelings in your daily life? Although this is highly personal, some examples might include your favorite scenic view from campus, your closest friends, or your favorite book. Have your camera or camera phone handy and take at least five photographs of such things today. It is important to take the activity seriously and not rush through it.

Writing prompt: After completing the photography exercise, reflect on your thoughts and feelings you had when (a) searching for appropriate subject matter, (b) taking the photographs, and (c) looking back at the photographs. Do you feel that it influenced your mood, emotions, and appreciation for things in your life? Why or why not?

Adapted from: Kurtz, J. L., & Lyubomirsky, S. (2013). Happiness promotion: Using mindful photography to increase positive emotion and appreciation.

Appendix A.2.7 Signature Strengths: List of Suggested Activities

Below is a list of suggested activities for signature strength that you selected. You do NOT have to use these activities! You can design whatever activity you think will work for you, as long as it allows you to employ one of your strengths.

1. **Curiosity and Interest in the World**
    a. Ask a question in class
    b. Discover new places
    c. Explore the stacks in the library; browse widely, or pick an interesting looking book and spend 20 minutes skimming it.
    d. Eat something new that you never otherwise would have tried
    e. Go to a meeting or hear a speaker (in person or virtually)
2. **Love of Learning**
    a. Discover a new place in Pittsburgh
    b. Read a newspaper other than the Pitt News
    c. Go to a professor's office hours without a question
    d. Ask a question in class
    e. Go to an online search engine like Ask Jeeves-ask a question and explore sites you never otherwise would have discovered
    f. Every day, read a chapter of a book that is not an assigned class text
    g. Read a book/watch a YouTube video about something you've always found intriguing but never found the time to learn more about
3. **Judgment, Critical Thinking and Open-Mindedness**
    a. Go to a multi-cultural group or event (in person or virtually)
    b. Play devil's advocate and discuss an issue from the side opposite to your personal views
    c. Take a roommate or friend out to lunch who is different from you in some way.

    d. Go to a different church or religious event
    e. Pick something you believe strongly, and think about how you might be wrong.
4. **Creativity, ingenuity, and originality**
    a. Keep a journal, work on a picture or poem
    b. Submit a piece to a literary magazine or newspaper
    c. Decorate a notebook or your room
    d. Pick one object in your room and devise another use for it rather than its intended use
    e. Find a new word (perhaps at dictionary.com) and use it creatively.
    f. Change your Facebook profile photo or take new photos
    g. Pick up a new hobby or foster an old one
5. **Social Intelligence**
    a. Meet one new person each day by approaching them
    b. Go into a social situation in which you would normally feel uncomfortable and try to fit in
    c. Whenever you talk with someone, try to figure out what his or her motives and concerns are.
    d. Encounter someone by themselves and by being friendly, include them in your group
6. **Perspective (Wisdom)**
    a. Get a quote a day online
    b. Give advice to an upset friend
    c. Think of the wisest person you know. Try to live today as that person would live.
    d. Look up prominent people in history and learn their views on important issues of their day and/or find a significant quotation that they said.
7. **Courage**
    a. Talk in class (if you don't normally)
    b. Go against peer pressure or social norms
    c. Stand up for someone even if you disagree with him/her.
    d. Ask someone you don't know very well to do something with you
    e. Introduce yourself to a stranger next to you in class
    f. Speak up for an unpopular idea (if you believe in it)
8. **Industry diligence and Perseverance**
    a. Finish work ahead of time
    b. Notice your thoughts about stopping a task, and ignore them. Focus on the task at hand.
    c. In class, resist daydreaming and distractions.
    d. Plan ahead - use a calendar for assignments and tests.
    e. Set a high goal (e.g., for exercise, or studying) and stick to it.
    f. When you wake up in the morning, make a list of things that you want to get done that day that could be put off until the next day. Make sure to get them done that day.
9. **Honesty, Authenticity and Genuineness**
    a. Refrain from telling small, white lies, to friends (including insincere compliments). If you do tell one, admit it and apologize right away.
    b. Monitor yourself and make a list of every time you tell a lie, even if it is a small one. Aim to make your daily list as short as you can.
    c. At the end of each day, identify something you did that was attempting to impress people, or put on a show. Resolve not to do it again.
10. **Zest, Enthusiasm, and Energy**
    a. Go out of your way to become more involved in an organization you are already a part of
    b. Take up a greater interest in one of your classes (like volunteering for a class activity)
    c. Do something because you want to, not because you are told.
    d. Get a good night's sleep and eat a good breakfast, to give yourself more energy during the day.

   e. Do something physically vigorous (e.g., jog, push-ups)

11. **Kindness and generosity**
    a. Leave a huge tip for a small check.
    b. Be a listening ear to a friend. Ask them how their day was and actually listen to the answer before telling them about your own day.
    c. Send an e-card or motivational quote to a friend.
    d. Pay the whole tab when you are out with friends.
12. **Capacity to Love and be Loved**
    a. Tell boyfriend/girlfriend/sibling/parent that you love them
    b. Send a loved one a card or e-card to say that you were thinking about him/her.
    c. Give loved ones a big hug and a kiss
    d. Write a nice note where someone you love will find it sometime during the day. Do this in a new place, or for a new person.
13. **Citizenship and Teamwork**
    a. Volunteer somewhere that interests you
    b. Take on added responsibility within an organization you are already a part of
    c. Pick up litter that you see on the ground
    d. Clean your suite, hall, or lounge (anywhere communal)
    e. Organize a hall/suite dinner
    f. Do your share in a group work/as a facilitator
14. **Fairness Equity and Justice**
    a. Allow someone to speak their peace while keeping an open mind by not passing judgment
    b. Stay impartial in an argument between friends despite your beliefs (be the mediator)
    c. Notice when you treat someone based on a stereotype or pre-conception; brainstorm ways not to do it again.
15. **Leadership**
    a. Organize something special for your friends or suitemates one evening.
    b. Organize a study group
16. **Modesty**
    a. Don’t talk about yourself at all for a full day.
    b. Dress and act modestly, so as not to attract attention to yourself.
    c. Find a way in which someone you know is better than you. Compliment him or her for it.
17. **Self-Control and Self-Regulation**
    a. Set aside a designated amount of time and ACTUALLY study in a quiet place.
    b. Clean or organize your room. Make sure that you pick up whatever mess you made during the day.
    c. Leave something unfinished on your plate that you usually regret eating afterwards.
    d. When something upsets you, attempt to block it out of your mind and instead focus on the good things in your life.
    e. Make a resolution to not gossip. When you feel the urge to talk about someone behind his or her back, remember your resolution and stop yourself before you talk.
    f. Make an agenda for today. Stick to that agenda.
    g. When you get overly emotional about something, give yourself space to calm down and calmly consider all of the issues again.
18. **Caution, Prudence and Discretion**
    a. During a conversation, think twice before saying anything. Weigh the probable effect of your words on others.
    b. Think about the motto “Better safe than sorry” at least three times a day. Try to incorporate its meaning into your day.

c. Before you decide to do something important, reflect on it for a moment and consider if you want to live with its consequences 1 hour, 1 day, or 1 year later.

19. **Forgiveness and Mercy**
    a. Think of someone that you found it very hard to forgive. Try to see the situation from their perspective. Then consider, if you had been the one to do the offensive act, would you have expected to be forgiven?
    b. Think about someone who made you mad, or who you have a grudge against. Then, think about why you are resistant to forgiving them. Then look at the situation from that person's point of view, and see whether you can forgive the person.
    c. Make contact with someone who has made you mad in the past. Let them know that you forgive them, or just be kind to them in your conversation.
    d. When someone does something that you do not understand, try to understand his or her intentions in the actions.
20. **Appreciation of Beauty and Excellence**
    a. Write down your thoughts about a piece of art, or something beautiful you see around grounds.
    b. Take a walk with a friend and comment on something pretty that you see
    c. Listen to music and enjoy the sound for its musical value. Or pick out the most moving music you know of, and listen to it appreciatively on headphones. Or ask a friend to recommend the most beautiful music he or she knows.
    d. Notice the things you see during the day that strike you as extremely beautiful, or skillful.
    e. Find something that makes you happy, in aesthetics or value, a physical activity or an object, and let it inspire you throughout the day.
    f. Browse through the art books or pictures online.
21. **Gratitude**
    a. Thank someone for something that you might otherwise take for granted (e.g., thanking the janitor who cleans your hallways).
    b. Keep a record of the number of times you use the words "thank you" today with the intention of using it more than you normally would.
    c. Call a parent/sibling/friend each day and thank him/her (e.g., for helping you to become who you are, or for always being there for you.)
    d. Send someone a "thank you" e-greeting.
    e. Leave a note on your roommate/apartment mate suitemate/hall mate that thanks them for something about them that you appreciate.
22. **Hope, Optimism, and Future-Mindedness**
    a. Think about a decision you have made today and how that might positively impact your life in the long run.
    b. When you are in a bad situation, turn it around to see the optimistic side of it. You can almost always find some good in a situation, regardless of how awful it seems at the time.
    c. Make a list of bad decisions you have made. Forgive yourself and move on in life realizing that you cannot go backwards, only focus on the present and future.
    d. Notice your negative thoughts. Counter them with positive thoughts.
    e. Reaffirm yourself that you can and will succeed at whatever you put your mind to.
23. **Spirituality and Sense of Purpose, and Faith**
    a. Relax and think about the purpose of life, and where you fit in.
    b. Think about the things you can do to improve the world or your community.
    c. Read a religious or spiritual book, or go to a religious service
    d. Explore different religions. You can do this by going to a library, looking on the Internet, or asking your friends about their religions.
    e. Spend a few minutes in meditation or prayer.
    f. Invest in a book of affirmations or optimistic quotes. Read a few.

24. **Humor and Playfulness**
    a. Make someone smile or laugh.
    b. Learn a joke and tell it to your friends.
    c. Watch a funny movie or TV show.
    d. Read the comics
    e. Learn a magic trick and perform it for your friends

Adapted from: Haidt, J. (2002). It's more fun to work on strengths than weaknesses (but it may not be better for you). *Manuscript retrieved from http://people. virginia. edu/~ jdh6n/strengths_analysis. doc*.

Appendix B Pilot Study 1 Questionnaires

Appendix B.1 Baseline Questionnaires

Demographic Questionnaires. participants will be asked to report their age, sex (assigned at birth; Male or Female), gender/gender identity, race, whether or not they are Hispanic (Yes or No), year in college (Freshman, Sophomore, Junior, Senior, or Senior +), and their major and minor areas of study. Socioeconomic status was measured as a proxy for circumstantial factors that can influence happiness (Lyubomirsky, Sheldon, & Schkade, 2005). Socioeconomic status was estimated by parental education and perceived parental social standing. Parental education was measured on a 1 (“did not complete high school”) to 9 (“doctorate”) scale (Gianaros, et al., 2008). Perceived parental social status will be assessed using an image of a ladder and asking participants to place themselves, their mother, and their father on a rung of the ladder that best represents where they would fit on the ladder. Those on the top of the ladder are best off and those at the bottom of the ladder are worst off (Adler et al., 2000; Goodman et al., 2007). Participants also reported the highest level of educational attainment for each of their parents. Socioeconomic status will *not* be indicted by self-reported parental income, as many college students may not know their parents’ income.

Medical history. Participants were asked if they are currently taking medications for any emotional disorders and, if so, to provide the name of the medication(s). Anxiety symptoms were assessed using the 7-item PROMIS –Anxiety –short form scale, whereas depressive symptoms were assessed using the 8-item PROMIS –Depression –short form scale (Pilkonis et al., 2011; Anxiety $\alpha = .89$; Depression $\alpha = .92$). Both instruments ask participants to rate how frequently they have felt a particular way within the last two weeks (*e.g., "*I felt uneasy" or "I felt like a failure") on a 1 (Never) to 5 (Always) scale. It is particularly important to measure depressive symptoms at baseline because depressed individuals tend to show *greater* improvement in happiness following positive psychological interventions (Sin & Lyubomirsky, 2009; Boiler et al., 2013).

Hedonic well-being. Hedonic well-being is defined by high positive affect, life satisfaction, and low negative affect (Diener et al., 1999). Positive and negative affect will be measured by two different instruments: the 20-item Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988; PA-few days $\alpha = .88$; NA- few days $\alpha = .83$; PA-general $\alpha = .84$; NA- general $\alpha = .83$), Positive and Negative Emotional Style Scale (PES and NES; Cohen et al., 2003; PES-few days $\alpha = .90$; NES- few days $\alpha = .83$; PES-general $\alpha = .86$; NES-general $\alpha = .84$). The PANAS provides a list of emotion words and asks the extent to which each emotion is experienced during a specified period of time. Although the PANAS is used frequently, its positive affect scale has been criticized for including non-emotion words (*e.g.*, strong) and focusing predominantly on high-arousal positive emotions (*e.g.*, proud and excited), without including low-arousal positive emotions (*e.g.*, calm and content; Pressman & Cohen, 2005). By contrast, the PES and NES scales include positively and negatively valanced emotion words that span the arousal continuum. Similar to the PANAS, the PES and NES ask participants to rate how accurately each adjective describes how they usually feel (Cohen et al., 2003). There are nine adjectives used to measure PES that fall into three subscales: vigor (lively, full-of-pep, energetic), well-being (happy, pleased, cheerful), and calm (relaxed, calm, at ease). Similarly, nine adjectives are also used to measure NES across three subscales: anxiety (on edge, nervous, tense), depression (sad, depressed, unhappy), and hostility (hostile, resentful, angry). All questionnaires assessing positive and negative affect at baseline and post-intervention will request participants to report their emotions both within the past two weeks and in general. In addition to assessing affect, life satisfaction will be measured by the 10-item PROMIS General Life Satisfaction questionnaire ($\alpha = .92$). This questionnaire asks to rate the extent to which participants agree with a particular statement (*e.g*, "My life is going well") on a 1 ('Strongly disagree') to 7 ('Strongly agree') scale (Salsman et al., 2014).

Well-being. Although the positive psychological intervention is aimed at increasing positive affect, it is possible that the intervention may influence eudaimonic or social domains of well-being. Eudaimonic well-being will be measured using the 42-item Psychological Well-being scale (Ryff, 1989; $\alpha = .93$). Within the Psychological Well-being scale, there are six subscales including: autonomy, environmental mastery, personal growth, positive relations with others, purpose in life, and self-acceptance. Each item states a life perspective and participants rate the extent to which they agree or disagree with the statement. In addition to eudaimonic and social well-being, optimism is a positive psychological trait that can further enhance well-being (Daukantaite & Zukauskiene, 2011; Zhang et al., 2013; Ho, Cheung & Cheung, 2010). Therefore, the Life Orientation Test – revised will be used to assess dispositional optimism (Scheier, Carver & Bridges, 1994; $\alpha = .82$). In contrast to other positive psychological interventions (*e.g.*, King, 2001), the current intervention does not directly target optimism; however, by measuring optimism, we can test whether any impacts of the psychological intervention on stress physiology occur *independent* of changes in optimism.

Social factors. Positive affect may have reciprocal relationships with social factors that could, together, impact health. Two aspects of social factors will be assessed: perceived loneliness, and social support. Loneliness will be measured using the 8-item UCLA Loneliness Scale (Russell, Peplau, & Ferguson, 1978; α = .84). The UCLA Loneliness Scale asks participants how frequently they feel a particular way on a 0 (“I never feel this way) to 3 (“I often feel this way”) scale. Finally, social support was assessed by the 12-Item Interpersonal Support Evaluation List (Cohen et al., 1985; α = .86). This scale provides statements about situations that might elicit social support and asks participants to rate each statement on a 1 (“definitely false”) to 4 (“definitely true”) scale.

Perceived Stress. Stress appraisals were assessed by the Perceived Stress Scale (Cohen, Kamarck, & Mermelstein, 1994; α = .85). The Perceived Stress Scale asks participants to indicate the frequency of stress appraisals (e.g., “feel unable to control important things in your life”) in the past month on a scale from 0 (‘Never’) to 4 (‘Very Often’).

Appendix B.2 Post-activity Questionnaires

On the days when participants complete their prompts, they were also be asked a few questions to assess mood, physical activity, sleep, loneliness, social connectedness, perceived stress, academic stress and frequency of using the intervention skills. To assess mood, all 18 items of the Positive and Negative Emotional Style scale were used (see above). Physical activity was assessed by asking “how many minutes of light physical activity did you do today (*e.g.,* walking to class, cleaning, chores, etc)?”. The second question asks, “how many minutes of moderate to vigorous exercise do you do today (*e.g.,* running, gym, sport, etc)?”. To assess sleep, participants reported both the total number of hours they slept the previous night and their overall sleep quality. Sleep quality was assessed on a 0 (‘Very bad’) to 4 (‘Very good’) scale. Participants rated their loneliness, social connectedness, perceived stress, and academic stress using a visual analogue scale to reflect how accurate each statement reflected the following statements: “Today I feel lonely or isolated,” “Today I feel connected to others,” “Today I feel stressed,” and “Today I feel nervous or overwhelmed about school". The final question will ask participants whether they have spontaneously used any of the intervention skills during the day. If so, a follow-up question will ask which skill(s) they used during the day.

Appendix B.3 Post-Intervention Questionnaires

Most questionnaires that were administered pre-intervention were readministered at post-intervention. Please see Table 1 for the complete list of the administration schedule for each questionnaire.

Appendix C Exploratory Analyses for Positive Psychological Intervention

Appendix C.1 Exploratory Aims

Exploratory Analysis 1. To assess whether changes in positive affect were more strongly associated with the use of particular positive psychological activity.

Rationale: The majority of positive psychological interventions that use a variety of positive psychological activities do not explore which activity or activities might be most associated with greater gains in positive affect. Therefore, we would like to explore the relationship between the types of positive psychological activities and increases in positive affect.

Exploratory Analysis 2. To assess whether the intervention influenced self-reported sleep quality or quantity and physical activity.

Rationale: Previous studies indicate that positive affect is associated with subjective reports of sleep and physical activity. As such, we will empirically test whether a two-week positive psychological intervention is associated with changes in self-reported sleep and physical activity.

Appendix C.2 Exploratory Analyses

Exploratory Analysis 1. Three analyses will be performed to assess whether changes in positive affect were more strongly associated with the use of particular positive psychological activities. First, we will calculate Pearson's correlation coefficients between the frequency that each activity was used and the change in positive affect from pre- to post- intervention. Change in positive affect will be calculated by computing the sum of the general and last few days versions of the PES and PANAS-PA for both baseline and post-intervention values. Then, baseline positive affect was subtracted from post-intervention values to indicate the change in positive affect.

Second, the difference in the percentage of positively valanced words that were written will be compared for each activity using a liner mixed effects model that includes repeated activity types (Level 1) within each participant (Level 2). A mixed effects model can accommodate for the missing data, which is expected because not every intervention participant completed each activity.

Third, a second linear mixed effects model was used to investigate the relationship between daily reported positive affect and the type of activity that was completed on that day. All analyses will only be conducted using the subset of participants who were assigned to the intervention group.

Exploratory Analysis 2. To assess whether the intervention influenced self-reported sleep quality or duration and physical activity, a two-way repeated measures MANOVA to compare group differences in sleep and physical activity across all time points (8 maximum) between groups. The two sleep items (quality and quantity) will be included in the same model as dependent variables. The two items of physical activity (light and moderate-to-vigorous) will also be included in a second model as dependent variables.

Appendix C.3 Exploratory Results

Exploratory Analysis 1: Type of Positive Psychological Activity

The activity that fewest participants completed was the Gratitude Letter (*N* = 56, 54.4%), followed by Acts of Kindness (*N* = 32, 31.1%), Savoring (*N* = 34, 33.0%), Best Future Self (*N* =

25, 24.3%), Signature Strengths (*N* = 19; 18.4%), and Three Good Things (*N* = 4; 3.9%). There was no difference in the number of missing observations between the different positive psychological activities (χ^2(25, *N* = 103) = 30.0, *p* = .22). Changes in positive affect were not associated with the frequency of any positive psychological activity (Signature Strengths: *r*(101) = .02, *p* = .81; Three Good Things: *r*(101) = -.06, *p* = .53; Acts of Kindness: *r*(101) = -.03, *p* = .80; Best Future Self: *r*(101) = -.05, *p* = .65; Gratitude Letter: *r*(101) = 0.12, *p* = .22 ;Savoring: *r*(101) = -.05, *p* = .59).

Next, the positive psychological activities were compared by the percentage of positive words written during their corresponding writing prompts. Results suggest that Signature Strengths (*M* = 6.2, *SD* = 3.4) resulted in a smaller percentage of positive emotion words relative to the Three Good Things (*M* = 7.2, *SD* = 2.9, *p* = .015) and Gratitude Letter (*M* = 8.2, *SD* = 2.5, *p* < .001) activities. In addition, Savoring (*M* = 5.9, *SD* = 2.8) also produced fewer positive emotion words relative to the Gratitude Letter (*p* < .001) , Three Good Things (*p* = .007), and Acts of Kindness (*p* = .04) activities.

Finally, we assessed the relationship between using each activity and their daily diary reported positive affect. Results suggest that Acts of Kindness (*M* = 19.3, *SD* = 7.7) were associated with greater daily positive affect relative to the Signature Strengths activity (*M* = 16.2, *SD* = 7.4, *p* = .02).

Exploratory Analysis 2: Health Behaviors

Sleep quality and duration correlated under the predetermined threshold of *r* = 0.50 (repeated measures *r*(1444) = .47, *p* < 0.001). Therefore, the relationship between positive affect and sleep quality and duration were assessed by two separate ANOVAs. There was no main effect of condition (*F*(1, 132) = 0.08, *p* = .78), no main effect of time (*F*(7, 924) = 1.30, *p* = .25), and no condition x time interaction ($F(7, 924) = 1.60$, $p = .13$) on sleep quality. Similarly, there was also no main effect of condition ($F(1, 132) = 0.55$, $p = .46$), no main effect of time ($F(7, 924) = 1.02$, $p = .42$), and no condition x time interaction ($F(7, 924) = 1.48$, $p = .69$) on sleep duration.

Light and vigorous-to-moderate physical activity correlated under the predetermined threshold of $r = 0.50$ (repeated measures $r(1445) = .07$, $p = .007$). Therefore, the relationship between positive affect and sleep quality and duration were assessed by two separate ANOVAs. There was no main effect of condition ($F(1, 98) = 0.08$, $p = .78$), no main effect of time ($F(7, 686) = 0.74$, $p = .64$), and no condition x time interaction ($F(7, 686) = 0.54$, $p = .80$) on light physical activity. Similarly, there was also no main effect of condition ($F(1, 107) = 0.04$, $p = .83$), no main effect of time ($F(7, 749) = 1.97$, $p = .30$), and no condition x time interaction ($F(7, 749) = 0.60$, $p = .75$) on moderate-to-vigorous physical activity.

Appendix D Study Modifications For the Remote TSST

<u>Modification 1:</u> In the previous study, participants received a phone call prior to their Zoom session to assess eligibility, to review and sign the consent form, and to schedule their Zoom visit. The current study will conduct this portion of the study on Zoom instead of by phone. At this time, participants will also be instructed on how to setup Zoom for the study, so that they are more familiar with the environment before the study visit.

<u>Rationale:</u> The purpose of including an additional Zoom visit before the rTSST (or control condition) is to give the participants time to habituate to participating with research over Zoom and to practice setting up Zoom for the study.

<u>Modification 2:</u> Previously, both control and stress participants remained in the main Zoom 'room' with the lead researcher during their speech and mental arithmetic tasks. During this study, stress participants will be placed in a breakout room with the two judges (in the stress condition). Control participants will remain in the main room with the lead researcher and their Zoom visit will not be recorded.

<u>Rationale:</u> The purpose of this modification is to keep the rTSST more consistent with in-person protocols. During the in-person TSST protocols, the lead experimenter brings the participant into a novel room with the judges to perform their speech and mental arithmetic tasks. There are two potential reasons why this step may be important to imitate during a remote version of the TSST. First, leading participants into a new room (or breakout room for the rTSST) may induce a sense of novelty that could reasonably increase perceptions of stress. Second, the participant may have positive or neutral interactions with the lead experimenter. As such, having the lead experimenter present during that task may serve as a source of social support that could

reduce perceptions of stress during the task (*e.g.*, Thorsteinsson & James, 1999). For these reasons, it may therefore be important that the lead experimenter remains in the main Zoom room while the participant enters a separate break out room with the two rTSST judges.

Modification 3: Previously, participants were asked to sit quietly while collecting baseline cardiovascular measures. During this study, participants will watch a neutral video during baseline cardiovascular measures.

Rationale: The purpose of adding a neutral video for the participants to watch during baseline is to reduce any discomfort or awkwardness participants might experience while sitting quietly on Zoom and to better standardize the environment during baseline for all study participants.

Modification 4: Previously, control participants had a conversation with the lead researcher during the speech task. During this study, control participants will be asked to read from an emotionally neutral script at their own pace.

Rationale: Some participants in the previous study deviated from the list of suggested topics to discuss during the speech task and instead discussed stressful events (*e.g.*, experiences with COVID). Discussing such emotionally valanced topics could have reasonably increased cardiovascular reactivity in the control group. Therefore, in an attempt to control for the emotional valance of the conversation, we will provide an emotionally neutral script for participants to read from during the speech task. Additionally, previous research suggests that having an observer present during a task can increase physiological responses to psychological tasks (Cacioppo et al., 1990). To minimize an influence of an observer on cardiovascular responses to the speaking task, the control participant will be told that the researcher is not evaluating their behavior, and will be asked to put the script on full screen so that they cannot see the researcher during the task.

Modification 5: Previously, participants were given three minutes to prepare for their speech task. Participants will now have five minutes to prepare for the speech task.

Rationale: The previous study aggregated cardiovascular data across the speech preparation and speech delivery periods. However, speaking itself increases blood pressure. As such, it is possible that any group differences in cardiovascular responses to the stressful nature of the task could be masked by differences in the frequency or rate of speaking. By lengthening the duration of the preparation period, we can collect 3 cardiovascular measurements during the preparation period, allowing us to look at speech preparation and speech delivery separately to understand whether the act of speaking is masking any group differences in cardiovascular reactivity in response to the stressful nature of the task.

Modification 6: The original protocol had participants interview for a potential job during their first speech task and interview for a promotion during their second speech task. We will modify the second speech task directions and instead ask participants to give a speech about various aspects of their personality (Gunnar et al., 2020).

Rationale: The test-retest reliability to induce blood pressure reactivity between the original tasks (job interview and promotion) were low (AUCi ICC = .34 - .49). One explanation may be that the tasks were too similar, and participants might have been better prepared to cope during the second rTSST. As such, we will change the instructions for the second rTSST speech task to a different domain to reduce any habituation that might have occurred in response to the tasks being too similar. Instead of interviewing for a promotion, participants will instead be asked to pretend that they are introducing themselves to their classmates.

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