Does Light Physical Activity Reduce Blood Pressure Responses to Laboratory Stressors?

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Does Light Physical Activity Reduce Blood Pressure Responses to Laboratory Stressors?

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Previous literature generally suggests that exaggerated blood pressure responses to stress, which is associated with increased risk for later cardiovascular disease (Chida & Steptoe, 2010), can be reduced after engaging in brief bouts of moderate-to-vigorous physical activity (Hamer et al., 2006). Observational work has shown that periods of light physical activity may also be associated with reduced blood pressure responses to stress in daily life (Thomas et al., 2019), however, the few experimental studies involving light physical activity have methodological limitations that temper conclusions. The current investigation sought to understand the effects of brief bouts of light physical activity on blood pressure responses to psychological stress. In a between-person, single-session experimental design, 179 healthy, young adults were randomized to 15 minutes of light physical activity, moderate physical activity, or sitting before engaging in a 10-minute computerized Stroop Color-Word Interference Task. Blood pressure readings were collected throughout the study session. Surprisingly, participants in the light physical activity group showed higher systolic blood pressure responses to stress than the control participants. These findings show that light physical activity may not be related to reduced blood pressure responses to stress in an experimental session involving healthy, college-aged adults and question the extent to which brief bouts of light and moderate physical activity may reduce blood pressure responses to stress when measured in an acute experimental session. Future work investigating the relationship between light physical activity and blood pressure responses to stress may be more productive after long-term interventions rather than in acute settings.

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1.0 Introduction

For decades, researchers have examined cardiovascular reactivity, defined as individual differences in the typical magnitude or pattern of hemodynamic changes in response to challenges or stressors, as a potential risk factor for cardiovascular disease (CVD). Stemming from this literature, the “reactivity hypothesis” proposes that repeated, exaggerated occurrences of cardiovascular reactivity contribute to adverse changes in the heart and vasculature that promote the development of CVD, including hypertension, atherosclerosis, and CVD events (Gianaros & Jennings, 2018; Manuck, 1994; Manuck et al., 1989; Manuck et al., 1990). Early prospective studies on the relationship between exaggerated cardiovascular reactivity to stress and future cardiovascular outcomes had been promising (see Krantz & Manuck, 1984), yet conclusions about such a relationship had been tempered by sparse, direct evidence available at that time. After years of accumulating evidence from prospective, longitudinal studies, a substantial body of evidence indeed shows that acute cardiovascular responses to laboratory-based mental stressors are predictive of CVD risk.

In the strongest support of the reactivity hypothesis to date, a comprehensive meta-analysis (Chida & Steptoe, 2010) of 31 prospective studies found that greater stressor-evoked cardiovascular reactivity, aggregated from multiple reactivity measures, was significantly associated with future incident hypertension (r = 0.10), elevated systolic blood pressure (SBP; r = 0.12), and elevated diastolic blood pressure (DBP; r = 0.07). When analyses were separated by cardiovascular predictor, only exaggerated SBP (r = 0.10) and DBP (r = 0.12) reactivity were associated with poor cardiovascular outcomes. These conclusions are consistent with past qualitative reviews on reactivity and disease development (Treiber et al., 2003), especially hypertension and atherosclerosis (Krantz & Manuck, 1984; Manuck, 1994). Altogether, the extant literature supports a small but significant association between cardiovascular reactivity, especially BP reactivity, and CVD risk.

1.1 Physical Activity and Cardiovascular Reactivity

Based upon the assumption that cumulative exposure to exaggerated stress-related blood pressure changes may account for the association between trait-like blood pressure reactivity and cardiovascular outcomes, interventions designed to reduce instances of exaggerated blood pressure responses to stress (BPRS)[1] could conceivably alter CVD risk. Despite decades of interest in blood pressure reactivity as a potential risk factor for CVD, however, efforts to reduce BPRS have received considerably less attention in this field. Further, there is mixed or scant evidence regarding the efficacy of any such intervention.

A variety of interventions have been explored in this literature, including both pharmacological (e.g., beta-blockers) and non-pharmacological treatments (e.g., stress management, biofeedback, music therapy). Most of the interest has centered on physical activity as a means of reducing cardiovascular responses to stress. Broadly defined, physical activity refers to bodily movement from skeletal muscles that results in energy expenditure. Physical exercise is a type of physical activity, consisting of planned, structured, and repetitive movements of an

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[1] Here, "blood pressure responses" rather than "blood pressure reactivity will be used. Reactivity is a term more consistent with trait-like patterns of BP changes during stress, whereas response better reflects momentary BP changes. We do not propose that individual bouts of physical activity reduce trait-like patterns of BP changes.

intensity level (commonly referred to as moderate-to-vigorous physical activity, or MVPA) that would be expected to improve or maintain physical fitness (Caspersen et al., 1985).

The cross-stressor adaptation hypothesis provides a framework to understand how exercise may explain changes in cardiovascular responses to psychological stressors. The cross-stressor adaptation hypothesis posits that the favorable adaptations to exercise that occur with physical fitness (e.g., reduced exercise-related blood pressure responses) should generalize to the to the individual's cardiovascular responsiveness to psychosocial stressors (Sothmann, 2006; Sothmann et al., 1996). Specifically, this hypothesis proposes that individuals with greater cardiorespiratory fitness, which involves multiple components (i.e., aerobic capacity, muscular strength and endurance, body composition, and flexibility; Caspersen et al., 1985) commonly measured by an objective fitness test (e.g., resting HR, VO_{2max}, treadmill test to exhaustion), should produce a more favorable pattern of cardiovascular responses during psychosocial stressors than less fit individuals.

The literature examining the effects of physical exercise on attenuated BPRS has predominantly focused on differences in cardiorespiratory fitness through cross-sectional (e.g., fit versus unfit) and longitudinal (improvements following exercise training) studies. However, reviews and meta-analyses on the relationship between cardiorespiratory fitness and BPRS have been inconclusive. For instance, two meta-analyses, each published in the same year, reached divergent conclusions. In one meta-analysis of 33 cross-sectional and longitudinal studies, Forcier and colleagues (2006) showed attenuated stress-related heart rate (HR) and SBP reactivity among physically fit individuals relative to physically unfit individuals. However, the more inclusive meta-analysis of 73 studies by Jackson and Dishman (2006) showed that fitness was related to slightly *greater* cardiovascular reactivity. These discordant findings suggest that our understanding of the role of physical fitness, and to a greater extent, physical activity and BPRS may be incomplete.

Rather than focusing on cardiorespiratory fitness, research involving acute bouts of physical activity may be a promising direction to pursue in order to understand the role of physical activity in attenuated BPRS. Experimental trials involving the acute effects of physical activity, specifically MVPA, on BPRS have been more consistent than studies examining fitness effects. In a systematic review and meta-analysis of 15 randomized controlled trials, Hamer et al. (2006) showed significant overall reductions in SBP and DBP reactivity to laboratory psychosocial stress tasks (effect sizes of 0.38 and 0.40, respectively) following acute bouts of physical activity compared to resting periods (within-subject designs) or among non-active controls (between-subjects designs). In the ensuing qualitative review of the literature, the authors reported that the effects of MVPA on reduced BPRS were more consistent when the stressor(s) was presented within 30 minutes after the conclusion of the activity bout.

These encouraging results are tempered somewhat by heterogeneity among results and in the characteristics of the included studies. First, significant effect sizes were observed only among 10 of the 15 included studies, suggesting that the effects of physical activity bouts and BPRS may not be consistently shown. However, these null findings may have resulted from underpowered analyses, as four of the five null studies had sample sizes of fewer than 25 subjects.

Second, there was substantial heterogeneity in the physical activity characteristics of the included studies in the Hamer and colleague's meta-analysis. Though most of the studies involved cycling, there was wide range of intensity (ranging from 50–100% of VO_{2max}) and duration (10 minutes to 2 hours) of physical activity employed in these studies. No firm conclusions were drawn in this review about whether these differences in intensity and duration have any bearing on the magnitude of BPRS reduction. For instance, Hamer and colleagues reported that 4 of 10 studies involving moderate activity bouts (defined as less than 60% VO_{2max} or 75% HRR) demonstrated significantly attenuated BPRS (Hobson & Rejeski, 1993; Rejeski et al., 1991; Rejeski et al., 1992; West et al., 1998) whereas 7 of 8 studies involving vigorous activity bouts (defined here as greater than or equal to 60% VO_{2max} or 75% HRR) demonstrated significant effects (Bartholomew, 2000; Boone et al., 1993; Brownley et al., 2003; Probst et al., 1997; Rejeski et al., 1991; Roy & Steptoe, 1991; Steptoe et al., 1993). However, most of the smaller, underpowered studies had used moderate physical activity bouts, and as the authors point out, positive findings were still observed in studies involving moderate intensities. Altogether, the heterogeneity of the studies included in this meta-analysis suggest that intensity does not necessarily moderate BPRS reduction, and the precise characteristics involved in attenuated BPRS following acute physical activity require further research.

Despite these limitations, these meta-analytic findings raise the possibility that engaging in brief bouts of physical activity before a stressor may have more consistent effects on reducing BPRS than changing fitness levels, per se. Individuals who engage in frequent bouts of physical activity are more likely to fall within a “post-activity window” when they experience a daily stressor than when less active individuals experience a period of stress. Observing blood pressure responses to stress within this post-activity window may be a critical requirement in the detection of an association between physical activity and BPR.

If the relationship between physical activity and blood pressure responses to stress is limited to the post-activity window, this may explain the inconsistencies in the literature on physical fitness and BPRS. Recent bouts of physical activity are commonly considered to be a confound of the relationship between fitness and cardiovascular reactivity, and participants are typically asked to abstain from MVPA in the hours prior to the reactivity testing in this fitness-reactivity literature. It is possible that these restrictions in stressor protocols artificially dampen our ability to detect temporally limited activity-related reductions on BP responses to stress. Study designs that test cardiovascular responses outside of this post-activity window, where the relationship between physical activity and stressor-evoked cardiovascular responses are most pronounced, may unintentionally hinder the evaluation of the effectiveness of exercise interventions in modifying cardiovascular responses in this literature. In contrast, testing physical activity occurring within this post-activity window may enhance detection of such an association.

1.2 Physical Activity and Blood Pressure Responses to Stress in Daily Life

Real-time measurements of daily stressors using ambulatory monitoring methods may be used to address the concern that the benefits of physical activity on stressor-evoked cardiovascular responses may be more pronounced if tested proximal to an activity bout. Emerging evidence from our laboratory supports the importance of physical activity in moderating the effects of cardiovascular responses to daily stressors (Thomas et al., 2019). In a large sample of 477 healthy, middle-aged adults, participants provided ambulatory blood pressure (ABP) and recorded their daily experiences, using electronic diary entries, on an hourly basis over four monitoring days. Measures of momentary Task Strain (high demand, low control) and Social Conflict (rating of recent social interaction quality) derived from these electronic diary entries were used as indices of daily psychosocial stressors. An accelerometry device worn during this period was used to create two indices of physical activity: weekly average activity (a between-person factor) and recent activity (30 minutes prior to each electronic diary; a within-person factor). We examined the interaction between the measures of physical activity and blood pressure responses to these two types of psychological stressors in the natural environment.

After controlling for time-varying confounds (e.g., posture at ABP reading, recent cigarette consumption), multilevel models showed that weekly physical activity moderated the effects of ABP responses to Task Strain (SBP: b = -1.65, p = 0.03; DBP: b = -1.30, p = 0.03) and Social Conflict (DBP: p = 0.02). Simple slope analyses revealed that periods of Task Strain were associated with significant increases in SBP (b = 1.14, p <.001) and DBP (b = 1.00, p < 0.001) for less physically active individuals (those whose activity levels placed them one standard deviation below the sample mean) but not for more active individuals (one SD above the mean; SBP: b = 0.19, p = .54; DBP: b = 0.25, p = .29) (see Figure 1). Similarly, periods of Social Conflict were associated with significant increases in DBP (b = 0.40, p = .011) for less physically active individuals but not for more active individuals (b = -0.11, p =.48) (see Figure 2).

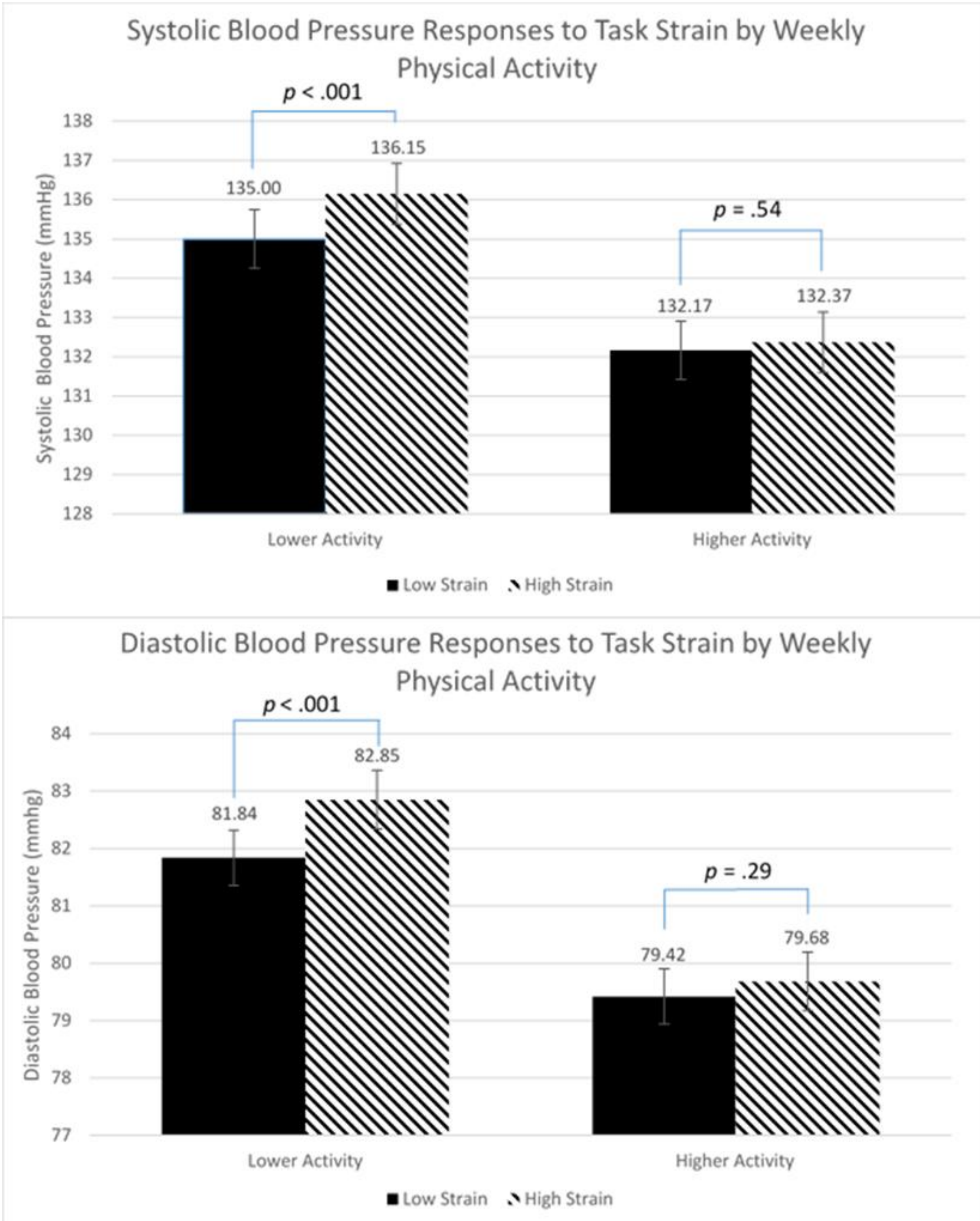

Figure 1. Blood Pressure Responses to Task Strain by Weekly Physical Activity

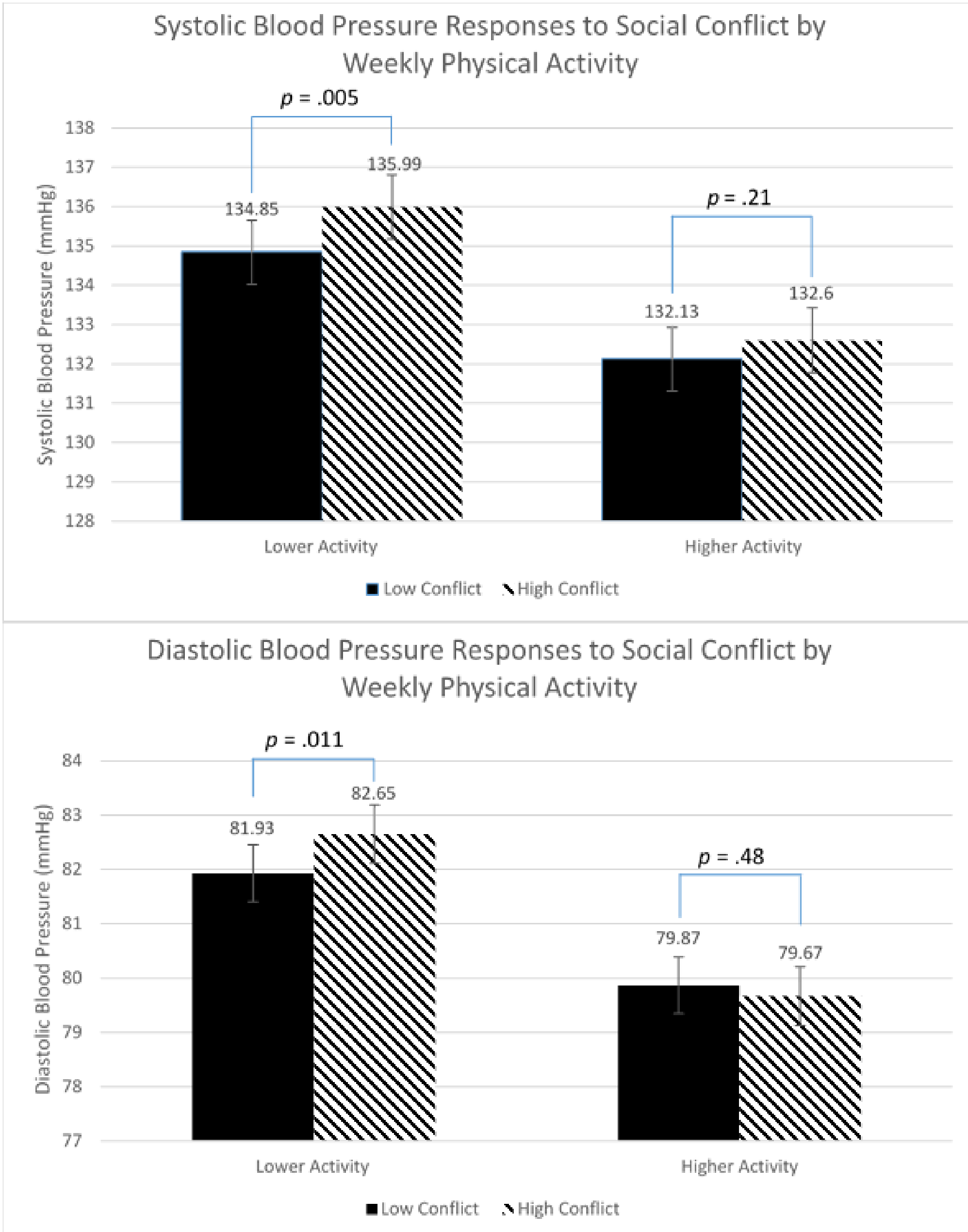

Figure 2. Blood Pressure Responses to Social Conflict by Weekly Physical Activity

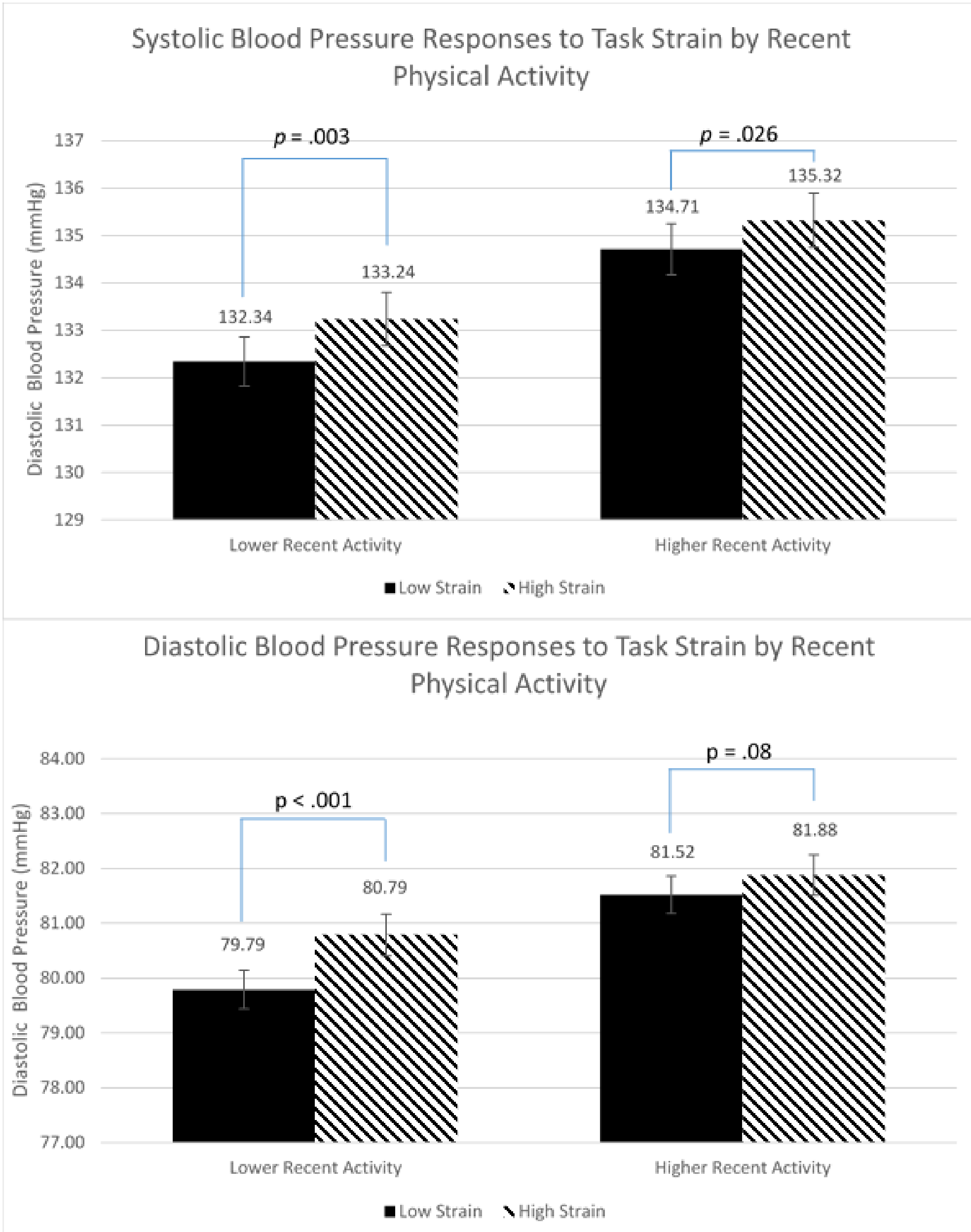

Figure 3. Blood Pressure Responses to Task Strain by Recent Physical Activity

In addition to these between-person findings, a significant within-person interaction emerged between Task Strain and recent physical activity on DBP (b = -0.45, p = .025). Simple slope analyses again suggested that periods of Task Strain were associated with significant increases in DBP (b = 1.00, p <.001) following periods of less activity in the prior 30 minutes. In contrast, Task Strain was not significantly associated with DBP elevations following periods of greater recent activity (*b* = 0.37, *p* = .08; see Figure 3). Notably, these models involving recent physical activity controlled for the effects of weekly average physical activity effects, suggesting that recent physical activity may exert some influences on BPRS over and beyond any effects associated with individual differences in habitual physical activity.

These data on the proximal relationship between activity and stress response are consistent with the notion that there may indeed be a "post-activity window," during which stress responding may be attenuated, and further suggest that characteristics of the activity bout that may be sufficient for reducing BPRS should be of interest. However, within-person effects were observed only with DBP responses to Task Strain in this study. SBP responses to Task Strain as well as both SBP and DBP responses to Social Conflict were non-significant in models involving recent physical activity. Due to the correlational nature of these data, it is unclear if these patterns of findings are due to differences in the nature of the stressor (mental versus interpersonal challenge), limited power due to fewer Social Conflict observations, or underlying hemodynamic mechanisms that explain effects for DBP rather than SBP. Obtaining data in a controlled, laboratory setting would provide us with an opportunity to examine more clearly the characteristics of activity bouts that seem to be most protective in reducing BPRS.

1.3 Potential Role of Light Physical Activity in Attenuating Blood Pressure Responses to Stress

In an attempt to better understand the physical activity characteristics associated with its moderating effect on SBP and DBP responses to daily psychosocial stress, exploratory analyses assessed physical activity levels in the 30 minutes prior to the blood pressure reading in the aforementioned study. Data were categorized into number of minutes spent in three conventional intensity ranges: sedentary (<1.5 metabolic equivalent units, or METs), light (1.5 – 3.0 METs), and moderate-to-vigorous activity (>3.0 METs). Controlling for time-varying covariates and main effects, multilevel models revealed that the number of minutes in sedentary and light activity moderated SBP as well as DBP responses to Task Strain. Simple slope analyses (above and below one standard deviation) revealed that periods with fewer minutes of recent light physical activity were followed by increases in SBP (p <.001) and DBP (p < .001) when stressors were present, whereas periods with more minutes of recent light activity were not associated with these increases (SBP: p = .28, DBP: p = .90). Unlike for Task Strain, no significant associations emerged involving Social Conflict. In contrast to the existing literature, the amount of time spent in MVPA was unrelated to attenuated BPRS. However, these null findings may have been a function of few observations of MVPA in this sample that resulted in insufficient statistical power. Conclusions cannot be drawn regarding MVPA in daily life in this sample, but these findings do suggest a potential role for light physical activity that is not frequently recognized in the literature on physical activity and BPRS.

The findings described above are consistent with emerging evidence on the cardiovascular benefits of light physical activity. As commonly defined in the literature, light physical activity involves a range of activity from walking at a slow or leisurely place (2 mph or less) to common household activities (e.g., cooking, washing dishes, laundry, gardening). Unlike other forms of physical activity, light physical activity can be performed virtually anywhere (e.g., house, street, office building) without need of specific equipment or clothing. In addition to its accessibility, light PA carries low musculoskeletal injury risk and no known risk of sudden severe cardiac events (Buchner et al., 2018). In light of its variety, accessibility, and low adverse health risk, it is no surprise that light physical activity is the most common type of activity in daily life (e.g., Colley et al., 2011).

In addition to its prevalence and logistical advantages, light physical activity may negate the deleterious health effects of sedentary behavior, a well-established risk factor for CVD. Replacing sedentary behavior with light physical activity reduces the risk of hypertension (Dempsey et al., 2016; Larsen et al., 2014; Zeigler et al., 2016; Zeigler et al., 2015), and arterial stiffness (Gando et al., 2010; O'Donovan et al., 2014) as well as CVD incidence and mortality (Autenrieth et al., 2011; Wannamethee et al., 1998). Based upon this growing literature, BPRS may be another outcome that is modified by light physical activity.

1.4 Intervention Implications of Light Physical Activity on BPRS

Given the evidence discussed above, interventions designed to increase the frequency of light physical activity bouts in daily life be effective in reducing blood pressure responses to daily psychosocial stressors. Such interventions featuring an already prevalent form of physical activity may address ongoing challenges of poor adherence and high attrition rates found with interventions featuring MVPA. It has been shown that 50% of people who start an exercise program will dropout within six months (Dishman, 1988), with a variety of factors including time, access to facilities or equipment, and energy (Chinn et al., 1999; Trost et al., 2002). In addition to its feasibility, the accessibility and low injury risk associated with light physical activity may be advantageous as an intervention for specific populations at risk for sedentary behavior, such as the socioeconomically disadvantaged, elderly, or those with chronic diseases (Mielke et al., 2017; O'Donoghue et al., 2016). Interventions featuring frequent light physical activity bouts may overcome concerns involving feasibility, accessibility, and injury risk common in interventions featuring more intensive physical activity.

Our previous work suggests that recent physical activity may reduce BPRS in the natural environment, and that light physical activity may be sufficient to produce such effects. Despite the potentially important implications of these findings, several limitations of this initial study need to be further addressed. First, the use of ambulatory assessments of physical activity introduce some measurement imprecision that raise questions about the nature of the physical activity that may have resulted in these apparent beneficial effects. The study used the SenseWear Pro3 armband (Body Media, Pittsburgh, PA; SenseWear Pro3) a small, non-invasive devise that integrates a bi-axial accelerometer with heat-related and skin conductance sensors to estimate energy expenditure. Specialized software estimates energy expenditure for each minute of data using activity-specific proprietary algorithms. Though the SenseWear armband devices provide accurate estimates of MVPA (Berntsen et al., 2010; Drenowatz & Eisenmann, 2011), one limitation is that the device is not sensitive enough to consistently determine the threshold (1.5 METs) between sedentary behavior and light physical activity. The SenseWear armband, compared to indirect calorimetry, has been shown to have low sensitivity of energy expenditure estimates during light physical activity (Calabr et al., 2014), and has been shown to underestimate energy expenditure during standing and sitting tasks (Reece et al., 2015). Thus, inferences about the number of minutes spent in light physical activity from these energy expenditure values should be interpreted with caution.

In addition to the physical activity measurement imprecision associated with ambulatory blood pressure assessment, the observational nature of the study design precludes inferences that differences in physical activity are causally related to reduced blood pressure responses to stress. It is possible the alternative explanations may explain the moderating effects of light physical activity on BPRS in the Thomas et al. (2019) study. For example, we cannot be certain that the type of stressors that typically occur following physical activity are otherwise comparable to the types of stressors that occur during sedentary periods, raising the possibility that third factors could account for the association observed. Furthermore, the time ordering of the stressor and physical activity bouts in this observational study cannot be precisely determined. As experiences of stress were recorded only in the 10 minutes preceding the BP reading, it is unknown if the stressor began before, during, or after the initiation of the physical activity bout. This uncertainty suggests that reverse causality cannot entirely be ruled out as an explanation for these findings.

Rather than correlational data, data obtained in a controlled setting using more precise measures of physical activity dose would address the problem of measurement precision, and rather than relying on observational data, use of an experimental design would address these concerns about causality. The use of a laboratory-based experiment could potentially facilitate the determination of a causal role of light physical activity in reduced BPRS as well as increase the experimental control over characteristics of light physical activity. Turning to the extant literature yields only four studies to the author’s knowledge that have experimentally tested the role of lower-intensity physical activity[2] in attenuating BPRS. Below is a summary and critique of the findings.

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[2] Under the correct conditions, standing may be considered physically active enough to be considered light physical activity. Standing does not meet the conventional definitions of sedentary activity. However, the existing evidence, albeit limited, suggests that standing may not influence blood pressure reactivity. Turner & Sherwood (1991) showed elevated BPRS during the standing condition compared to seated condition, whereas Waldstein, S. R., Neumann, S. A., & Merrill, J. A. (1998). Postural effects on hemodynamic response to interpersonal interaction. *Biological Psychology, 48*(1), 57-67. failed to find significant differences in SBP or DBP reactivity to an interpersonal laboratory

1.5 Extant Literature on Lighter Physical Activity Bouts and Reduced BPRS

In Alderman et al. (2007) 90 young, habitually physically active adults engaged in 30 minutes of low intensity activity[3] (50-55% VO_{2max}), high intensity activity, (75-80% VO_{2max}), and a sedentary control condition in a counterbalanced, within-person design. Participants were randomly assigned to be exposed to a mental arithmetic task, the laboratory stressor used in this study, at 5, 30, or 60 minutes following each level of activity (seated, low activity, and high activity). For the low intensity condition, MANOVA and post hoc analyses revealed that attenuated SBP and DBP responses was observed at 5 minutes following physical activity compared to the seated condition, and this attenuation persisted 30 minutes post-activity only for SBP responses[4].

In Taylor and Katomeri (2006), 60 temporarily abstinent, healthy smokers were randomized to 15 minutes of brisk walking (n = 31) or a passive control group (n = 29). Following a two-minute warm-up period at 2.48 miles per hour, participants engaged in walking at a semi-preferred intensity followed by a two-minute cool down period. SBP and DBP were assessed before and after three stressor tasks: a computerized Stroop word-color interference task, a speech

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stressor task between 15-minute seated and standing conditions. In light of these null findings, this project will not examine standing as an activity.

[3] Per direct correspondence with the first author on June 20, 2019, the exercise sessions were performed on a treadmill. In particular, the activity type of the low intensity session was consistent with jogging for most participants.

4For the high intensity condition, attenuated SBP and DBP reactivity was observed at 5 and 30 minutes post-activity, and SBP reactivity continued to be reduced at 60 minutes post-activity. SBP reactivity was lower in the high intensity condition than in the low intensity condition.

task, and a smoking cue. Stressor tasks occurred 10 minutes after the treatment session, and each stressor task was separated by 10 minutes of recovery. Univariate ANCOVAs (controlling for pre-stressor BP) revealed that participants in the brisk walking group showed attenuated SBP and DBP responses to the Stroop and speech tasks compared to the control group.

Adopting a similar protocol as Taylor and Katomeri (2006), Taylor and Oliver (2009), examined reductions in BPRS following 15 minutes of brisk walking in a sample of 25 regular chocolate eaters in a counterbalanced, within-person design. Participants were exposed to the Stroop task and a chocolate craving task following 15 minutes of brisk walking and a passive control period. Consistent with the prior study, fully repeated ANOVAs showed significant reductions in SBP and DBP responses to the Stroop task following the brisk walking bout.

The final study, Ledochowski et al. (2015) assessed 47 overweight, sugary snack consumers, in random order, to 15 minutes of brisk walking and a passive control session. Stressor tasks involved the Stroop as well as handling sugary snacks without consumption. However, each stressor task here failed to elicit an increase in mean sample SBP or DBP in either walking or control condition, thus preventing interpretation of any physical activity-related influences on BPRS. These findings were inconsistent with the previously cited studies despite the use of a similar physical activity and stressor protocols.

1.6 Limitations to the Extant Literature

Though these studies generally suggest that physical activity bouts attenuate blood pressure responses to standardized stressors, it is unclear whether the prescribed activity featured within these studies truly fall within conventional light physical activity ranges. This distinction is important. If these prior studies had only measured the lower end of moderate physical activity, then these studies only corroborate the conclusions of the Hamer meta-analysis involving MVPA, leaving the question about the extent to which *light* physical activity reduces BPRS unanswered. Below we evaluate the prior work in the context of conventional standards for physical activity intensity ranges.

According to the American College of Sports Medicine (2017), light physical corresponds with the following objective and subjective measures:

- 57-64% HR_{max}, the percentage of maximal heart rate.
- 30-40% HRR, the percentage of heart rate reserve (HR_{max} − resting HR).
- 37 – 45% VO_{2max}, the percentage of maximal oxygen uptake.
- 9 (“very light”) to 11 (“fairly light”) rating on Borg’s Ratings of Perceived Exertion (RPE), a self-reported exercise intensity index.

With these values in mind, the aforementioned studies may have involved more intensive physical activity bouts than what is considered to be light intensity physical activity by these standards.

For the Alderman study (2007), the targeted 50-55% VO_{2max} of low intensity exercise condition is more consistent with the moderate intensity exercise range (46-64% VO_{2max}). In both Taylor and Katomeri (2006) and Taylor and Oliver (2009), the targeted physical activity was to be moderate-intensity brisk walking, yet the sample mean RPE of 10.9 and 11.6, respectively, each correspond with a “fairly light” intensity range. As the physical activity was conducted at a semi-preferred pace, and no other measure of activity intensity was reported, the true intensity of these two studies are unknown. Thus, it is unclear whether the few studies on this topic had indeed employed physical activity bouts in the light or moderate physical activity ranges, the latter of which has already been established by the Hamer meta-analysis to be related to attenuated blood pressure responses to psychosocial stressors. If anything, these papers suggest that shorter bouts (i.e., 15 minutes) of moderate activity bouts are sufficient to reduce BPRS.

1.7 Potential Mechanisms Linking Light Physical Activity with Reduced and Blood Pressure Responses to Stress

Why should bouts of light physical activity be linked with reduced BPRS? Though no studies to date have examined the mechanisms by which light physical activity may result in attenuated BPRS, the known physiological parameters involved in blood pressure reactivity may provide us with some clues as to why we should expect such effects. Provided below is a brief review of the hemodynamic changes during and after bouts of aerobic physical activity that may influence subsequent BPRS. Note that most of our understanding on these processes extend from MVPA. Light physical activity evokes these same mechanisms but to a lesser extent; findings involving light physical activity are specified below where possible.

The cardiovascular system undergoes multiple, concurrent adjustments to provide adequate supply of oxygen and other nutrients to local peripheral tissues, particularly the activated muscles, during acute bouts of aerobic physical activity. It is well known that cardiac output (CO) and heart rate (HR) drastically increase at the onset of physical activity (MacDonald, 2002), and these changes are proportional to the intensity of the activity (Guyton & Hall, 2000; Rowell, 1986). Concurrent with this activity in the heart, vasoconstriction in arterioles and small arteries in tissues not involved in the physical activity bout provide greater venous return to the heart, and vasodilation occurs in the activated muscles to ensure adequate flow of oxygenated blood to meet the enhanced oxygen demand.

The increase in these cardiac mechanisms as well as the vasoconstriction in non-active arteriole beds result in pronounced increases in SBP during physical activity. Unlike its effects on SBP, aerobic activity may evoke minimal increases or even decreases in DBP due to the substantial vasodilation in active muscles. For instance, Kaufman et al. (1987) showed substantial increases in SBP (approximately 20 mmHg) but unchanged DBP levels after 10 minutes of walking at a lower end of a moderate-intensity range in normotensive and hypertensive adults.

During the period immediately following physical activity ("recovery"), diastolic BP is relatively unchanged. However, the pronounced increases in SBP shown during physical activity are short-lived. Systolic BP values normally returns to pre-activity resting levels within 6 minutes after the end of maximal exercise testing (Fletcher et al., 2001). Young adults in particular show a relatively fast rate of recovery. For instance, in a large sample of healthy, non-athletic adults, young males and females (mean age = 21) were monitored for systolic blood pressure recovery after mild (50% age-predicted HR_{max}) and moderate cycling bouts (70% age-predicted HR_{max}). In this sample, males returned to baseline systolic values within 5.8 (*SD* =1.08) and 5.6 minutes (1.08) for mild and moderate activity, respectively. Females returned to baseline SBP within 5.1 (0.94) and 5.1 (0.84) minutes of mild and moderate activity, respectively (Dimkpa & Ugwu, 2009).

Though blood pressure returns to pre-activity baseline values relatively quickly, other physiologic changes that emerge during recovery from physical activity may take somewhat longer to return to baseline. The most noteworthy of these processes involves reduced sympathetic activity during the post-activity recovery period. Such reductions may contribute to attenuated BPRS after an activity bout. Outlined below are select processes that contribute to reduced sympathetic activity following physical activity.

First, the sensitivity of the baroreflex is reduced during this recovery period for approximately 10 to 30 minutes (Niemela et al., 2008; Piepoli et al., 1993; Somers et al., 1985) to allow the baroreflex to shift to a new operational point. This "resetting" of the baroreflex results in reduced muscle sympathetic nerve activity following physical activity (Floras et al., 1989; Halliwill et al., 1996). In addition to reductions in sympathetic outflow, the transduction of sympathetic outflow into vascular resistance is also blunted following physical activity. During recovery from moderate physical activity, the relationship between sympathetic activity, as indexed by increases in muscle sympathetic nerve activity during isometric hand grip (a task known to elicit sympathetic activity), and vascular resistance was shown to be attenuated relative to effects observed during a resting condition (Halliwill et al., 1996). As this vascular response would otherwise rise in parallel with increased sympathetic activity, these findings suggest that sympathetic activity is less likely to be transduced into vasoconstriction during recovery periods.

Finally, changes in the local release of histamine following physical activity have been observed for decades (Anrep & Barsoum, 1935; Duner & Pernow, 1958). Such changes are known to have a vasodilator effect and may influence sympathetic activity following physical activity. For instance, histamine infusions can inhibit sympathetic nerve function to the myocardium as evidenced by the impairment of the cardioacceleration resulting from cardiac nerve stimulation in dogs (Lokhandwala, 1978). As reduced sympathetic activity may contribute to changes in BPRS, these processes involved in inhibited sympathetic activity following physical activity may play a role in the suppressed cardiovascular responses to stressors occurring during physical activity recovery periods.

1.8 Is Postexercise Hypotension Relevant to BPRS?

A final cardiovascular effect of a single bout of physical activity worth mentioning are the well-known reductions in SBP and DBP below pre-exercise levels. Coined “post-exercise hypotension,” these reductions can be sustained one to two hours following aerobic activity (Halliwill et al., 2013; Kenney & Seals, 1993; MacDonald, 2002). Despite its prevalence in the literature as plausibly accounting for attenuated BP responses to stress following physical activity, post-exercise hypotension has not been consistently observed in prior work. Among the studies that have shown reduced blood pressure responses to stress following an activity bout cited in the Hamer and colleagues meta-analysis, only four studies showed evidence of post-exercise hypotension (Probst et al., 1997; Rejeski et al., 1992; Rogers et al., 1996; Steptoe et al., 1993) while most do not (Bartholomew, 2000; Brownley et al., 2003; Hobson & Rejeski, 1993; Rejeski et al., 1991; Roy & Steptoe, 1991; West et al., 1998). These generally null findings may be explained by the inconsistent observation of post-exercise hypotension in normotensive populations; post-exercise hypotension has been more consistently observed in borderline hypertensive and hypertensive populations (MacDonald, 2002). The absence of post-exercise hypotension in the presence of reduced BP responses to stress following acute bouts of physical activity suggests that post-exercise hypotension is unlikely to link light physical activity to reduced BPRS.

1.9 Current Investigation

In sum, accumulating evidence suggests that acute bouts of moderate physical activity may reduce blood pressure responses to psychosocial stress, and physiologic data examining post-activity changes in sympathetic activity provide a plausible mechanism accounting for this change. Our ambulatory work suggests that light physical activity, in particular, may play a role in reducing blood pressure responses to stress during daily life, but the observational nature of the study as well as measurement error precludes firm conclusions. A few experimental studies have examined the role of bouts of light physical activity in attenuated BPRS, but the aforementioned methodological limitations associated with these studies temper the conclusions that may be drawn from them. Taken together, the extent to which light physical activity plays a role in reduced blood pressure responses to stress is not established. The current investigation seeks to better understand the role of light physical activity bouts in attenuating blood pressure responses to psychosocial stressors using an experimental design. Here, the physical activity bout will be closely monitored to ensure that the activity indeed is consistent with light physical activity.

Study Design. Methodological barriers in this field and research questions at hand raise a number of questions that warrant careful consideration for the current study design. Within-person designs are generally preferred for their greater statistical power and fewer confounds (e.g., demographic differences), however, blood pressure responses to repeated administration of the same laboratory stressor tasks are prone to habituation. In this context, changes in blood pressure responding that occur following repeated administration of a stressor may be due to either the effects of an experimental manipulation (physical activity bout) or due to habituation. On the other hand, use of a between-person designs involving BP responses to stressors would not require us to control for habituation due to the single measurement of BPRS. Though a between-person design may introduce potential pre-existing group differences necessitating a larger sample size in order to detect effects, this study will incorporate a between-person design due to its simplicity. Use of a homogeneous sample, such as an undergraduate research pool, and random assignment can address concerns about pre-existing group differences between the physical activity and control groups.

This current investigation proposes a three-group between-person design. All participants will undergo a reactivity testing period during which participants will be exposed to a series of standardized laboratory stressors. In the first group ("light physical activity"), the reactivity testing period will be preceded by a period of light walking. In the second group ("moderate physical activity"), the reacting testing will be preceded by a period of brisk walking. In the third group ("control"), the reactivity testing will be preceded by a period of seated sedentary time equivalent to the time demands for the light and moderate physical activity groups.

Rather than a two-group design (i.e., light vs. control), we reason that the inclusion of a moderate physical activity group better aligns this proposed study with the existing literature, while adding further context to interpret the light physical activity findings. For instance, null findings in the light physical activity group but positive findings in the moderate physical activity group would suggest that any activity-related reductions in BPRS are limited to higher intensity physical activity bouts typically employed in the literature. Additionally, the inclusion of two physical activity intensity groups allows us to address whether any activity-related reductions in BPRS are equivalent across groups, thus suggesting that any intensity of walking is effective at reducing BPRS, or if there exists a dose-response relationship between physical activity intensity and BPRS reduction (e.g., a larger reduction for the moderate physical activity group compared to the light physical activity group). In addition to enhancing the interpretability of these findings, the inclusion of a moderate physical activity groups permits us to compare the magnitude of any BPRS change by the level of physical activity bout intensity. Note that because the difference between the two physical activity groups is not expected to be large, the power to detect such effects may be limited. Rather, this study will be powered to detect differences between each of the physical activity groups and the control group.

Physical activity bout. The physical activity manipulation will consist of a 15-minute bout for both light and moderate walking conditions. As an interest of this current work is to extend our ambulatory assessment findings, this physical activity type was chosen over other types of aerobic activity (e.g., cycling) to be consistent with the physical activity that was likely to have occurred in daily life. Regarding the 15-minute bout duration, two lines of evidence informed this decision. First, this bout duration was chosen to be consistent with two other published works demonstrating reduced BP responses to stress following 15 minutes of moderate intensity physical activity in the form of brisk walking (Taylor & Katomeri, 2006; Taylor & Oliver, 2009).

Second, we re-analyzed our ambulatory assessment data to gain insight on whether 15 minutes of light physical activity may be sufficient to influence BPRS. Recall that our simple slope analyses reported earlier showed that one standard deviation (*SD* = 6.8) below the sample mean (*M* = 8.01) was associated with increases in SBP and DBP responses to periods of Task Strain, but this relationship was not found at one standard deviation above the sample mean. These values adjusting for the standard deviation corresponded approximately with 15 minutes versus 2 minutes of light physical activity. In a re-analysis of these simple slopes, we added and subtracted values from the sample mean (*M* = 1.98) such that “more light physical activity” was consistent with 10 minutes of light physical activity (and “less” light physical activity aligned with 6 minutes). This re-analysis again showed that lower range of light physical activity was associated with significant increases in SBP (p = .0017) and DBP (p = .0003) responses to period of Task Strain. Unlike the original simple slopes, the unit increase consistent with 10 minutes of light physical activity also was related to significant increases in SBP (p = .036) and DBP (p = 0.045) responses. This re-analysis provides preliminary evidence to suggest that 15 but not 10 minutes of light physical activity may be associated with reduced BPRS. Prior experimental studies involving 15-minute bouts of physical activity as well as our data involving 15 minutes of light physical activity suggest that a 15-minute bout of light physical activity may be an adequate threshold to detect physical activity-related changes in BPRS.

1.9.1 Will the pre-stressor baselines be equivalent across groups?

An important assumption to address is that the baseline blood pressure values after the physical activity bout or sitting period and prior to the reactivity testing sessions are equivalent across groups. Violation of this assumption, such as elevated BP in the physical activity groups, would reduce confidence that any group differences in BP responding to the stressors could be attributed to the activity bout rather than different starting BP values. There are two questions: 1) Will the BP values in the two PA groups return to their pre-activity BP baselines before the start of the stressor tasks; and 2) Will the control group participants not have elevated BP resulting from the prolonged sitting, which itself could be a confound?

Regarding the first question, several sources of evidence suggest BP values do return to the pre-activity baseline prior to the stressor tasks. First, the studies included in the Hamer meta-analysis do not suggest that BP at the end of the activity bout recovery period (and thus before the stress tasks) was elevated relative to the pre-activity baseline. Studies here reported a return to pre-activity baseline after recovery periods lasting 10 minutes (Szabo et al., 1993), 20 minutes (Hobson

& Rejeski, 1993; West et al., 1998) and 30 minutes (Brownley et al., 2003; Rejeski et al., 1991), and four studies showed *reduced* BP by the end of the recovery period (Boone et al., 1993; Probst et al., 1997; Rejeski et al., 1992; Steptoe et al., 1993). Second, the exercise physiology literature cited earlier suggests that SBP returns to baseline relatively rapidly following mild and moderate physical activity in young, healthy adults.

Finally, we have recently collected pilot data (N = 10, 90% female, mean age = 26.7, mean height = 63.8 inches) that address this question[5]. Following a 10-minute baseline period, with BP readings taken at 6, 8, and 10 minutes, participants walked at a light pace (<60% age-predicted HR_{max}) followed by up to 30 minutes of recovery, during which BP readings were collected every 4 minutes (at 4, 8, 12, 16, 20, 24, 28, and 30 minutes). This protocol was repeated for brisk walking (70-75% HR_{max}) in the same sample. Treadmill speed and/or grade were titrated in order to achieve the targeted HR throughout the activity sessions. The sample average HR_{max} was 69.9%, with 4 of 10 individuals achieving an average HR_{max} between 70-75%. However, the sample average and all 10 pilot participants achieved an average HR_{max} that met the ACSM criteria for moderate physical activity (64 to < 76% HR_{max})[6]. See Table 1 for more detail.

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[5] Due to the individual's time constraints, ID9 only completed the moderate physical activity portion of this pilot project. Thus, the reported analyses include 9 individuals for the light physical activity condition and 10 individuals for the moderate physical activity condition.

[6] I may have started at too low of a speed (3.0 mph) for the first five participants, in which three did not achieve an average HRmax of 70-75%. It is likely that they would have achieved the average targeted HR range had I started them at a higher starting speed.

Table 1. Heart Rate Pilot Data for Light and Moderate Physical Activity Bouts

Table 1 . Heart Rate Pilot Data for Light and Moderate Physical Activity Bouts

	Light Physical Activity																			
	ID1		ID2		ID3		ID4		ID5		ID6		ID7		ID8		ID9		ID10	
	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax
Minute 1	110	57.0%	93	48.7%	85	43.6%	101	52.1%	99	51.3%	87	45.5%	83	43.0%	102	51.8%			115	58.4%
Minute 2	115	59.6%	101	52.9%	82	42.1%	95	49.0%	97	50.3%	85	44.5%	82	42.5%	103	52.3%			112	56.9%
Minute 3	113	58.5%	96	50.3%	94	48.2%	88	45.4%	106	54.9%	90	47.1%	80	41.5%	102	51.8%			113	57.4%
Minute 4	118	61.1%	103	53.9%	91	46.7%	103	53.1%	98	50.8%	88	46.1%	83	43.0%	99	50.3%			112	56.9%
Minute 5	114	59.1%	95	49.7%	102	52.3%	97	50.0%	102	52.8%	93	48.7%	79	40.9%	99	50.3%			112	56.9%
Minute 6	123	63.7%	107	56.0%	87	44.6%	100	51.5%	114	59.1%	89	46.6%	84	43.5%	98	49.7%			113	57.4%
Minute 7	112	58.0%	102	53.4%	103	52.8%	98	50.5%	103	53.4%	88	46.1%	84	43.5%	99	50.3%			114	57.9%
Minute 8	108	56.0%	102	53.4%	93	47.7%	101	52.1%	110	57.0%	98	51.3%	87	45.1%	102	51.8%	Not Collected		113	57.4%
Minute 9	114	59.1%	102	53.4%	95	48.7%	94	48.5%	109	56.5%	92	48.2%	88	45.6%	95	48.2%			112	56.9%
Minute 10	118	61.1%	96	50.3%	99	50.8%	101	52.1%	108	56.0%	91	47.6%	86	44.6%	98	49.7%			112	56.9%
Minute 11	115	59.6%	98	51.3%	109	55.9%	104	53.6%	110	57.0%	93	48.7%	85	44.0%	96	48.7%			114	57.9%
Minute 12	115	59.6%	103	53.9%	109	55.9%	102	52.6%	114	59.1%	89	46.6%	83	43.0%	94	47.7%			115	58.4%
Minute 13	112	58.0%	97	50.8%	100	51.3%	97	50.0%	112	58.0%	97	50.8%	82	42.5%	96	48.7%			112	56.9%
Minute 14	111	57.5%	103	53.9%	107	54.9%	116	59.8%	117	60.6%	96	50.3%	85	44.0%	97	49.2%			113	57.4%
Minute 15	113	58.5%	99	51.8%	98	50.3%	107	55.2%	120	62.2%	91	47.6%	86	44.6%	93	47.2%			113	57.4%
Person-Level Means	114.1	59.1%	99.8	52.3%	96.9	49.7%	100.3	51.7%	107.9	55.9%	91.1	47.7%	83.8	43.4%	98.2	49.8%			113.0	57.4%
	Moderate Physical Activity																			
	ID1		ID2		ID3		ID4		ID5		ID6		ID7		ID8		ID9		ID10	
	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax	HR	% Hrmax
Minute 1	116	60.1%	11	5.8%	96	49.2%	117	60.3%	110	57.0%	114	59.7%	105	54.4%	124	62.9%	118	60.8%	139	71.6%
Minute 2	122	63.2%	114	59.7%	116	59.5%	117	60.3%	110	57.0%	121	63.4%	105	54.4%	122	61.9%	121	62.4%	150	77.3%
Minute 3	127	65.8%	117	61.3%	118	60.5%	125	64.4%	118	61.1%	117	61.3%	122	63.2%	121	61.4%	127	65.5%	149	76.8%
Minute 4	130	67.4%	124	64.9%	126	64.6%	135	69.6%	124	64.2%	105	55.0%	126	65.3%	125	63.5%	132	68.0%	144	74.2%
Minute 5	132	68.4%	132	69.1%	131	67.2%	143	73.7%	136	70.5%	116	60.7%	132	68.4%	125	63.5%	149	76.8%	144	74.2%
Minute 6	143	74.1%	137	71.7%	139	71.3%	143	73.7%	136	70.5%	125	65.4%	131	67.9%	125	63.5%	141	72.7%	147	75.8%
Minute 7	147	76.2%	138	72.3%	136	69.7%	138	71.1%	141	73.1%	130	68.1%	135	69.9%	131	66.5%	148	76.3%	144	74.2%
Minute 8	145	75.1%	140	73.3%	135	69.2%	147	75.8%	144	74.6%	130	68.1%	139	72.0%	132	67.0%	146	75.3%	140	72.2%
Minute 9	149	77.2%	147	77.0%	140	71.8%	143	73.7%	141	73.1%	126	66.0%	143	74.1%	138	70.1%	152	78.4%	138	71.1%
Minute 10	142	73.6%	142	74.3%	141	72.3%	151	77.8%	146	75.6%	126	66.0%	144	74.6%	136	69.0%	150	77.3%	139	71.6%
Minute 11	146	75.6%	146	76.4%	141	72.3%	149	76.8%	141	73.1%	143	74.9%	143	74.1%	133	67.5%	144	74.2%	134	69.1%
Minute 12	146	75.6%	143	74.9%	143	73.3%	142	73.2%	138	71.5%	147	77.0%	145	75.1%	148	75.1%	155	79.9%	134	69.1%
Minute 13	147	76.2%	147	77.0%	143	73.3%	142	73.2%	141	73.1%	143	74.9%	140	72.5%	140	71.1%	137	70.6%	136	70.1%
Minute 14	139	72.0%	139	72.8%	139	71.3%	137	70.6%	141	73.1%	138	72.3%	137	71.0%	138	70.1%	135	69.6%	136	70.1%
Minute 15	142	73.6%	134	70.2%	146	74.9%	136	70.1%	145	75.1%	135	70.7%	136	70.5%	140	71.1%	136	70.1%	133	68.6%
Person-Level Means	138.2	71.6%	127.4	66.7%	132.7	68.0%	137.7	71.0%	134.1	69.5%	127.7	66.9%	132.2	68.5%	131.9	66.9%	139.4	71.9%	140.5	72.4%

Note . Green background indicates that the average person-level HR was within the prescribed range, and blue bakcground indicates that the HR was below the prescribed range. Group-Level Mean HRmax is 51.9% for light physical activity and 69.3% for moderate physical activity.

To maximize reliability, the mean of the three baseline values were compared to the mean of two adjacent recovery values (e.g., mean of 4- and 8-minute recovery BP values, mean of 8- and 12-minute recovery BP values, etc.) for each of the light and moderate activity groups. A series of paired dependent t-tests reveal that at a group level, there were non-significant differences between baseline and SBP values at the 4 to 8 minute mark and for DBP values at the 8-12 minute mark following light activity. Following moderate activity, there were no significant differences between baseline and SBP values at the 8 to 12 minute mark and DBP values at the 12-16 minute mark. An analysis of the individual values suggests that there were non-significant differences in SBP and DBP values at the 4- and 8-minute readings, respectively, following light physical activity and at the 12-minute reading for SBP and DBP values following moderate physical activity. These pilot data suggest that BP returns to baseline following the light and moderate forms of physical activity within 12 to 16 minutes[7].

Regarding the control condition concern, a review of the literature suggests that the sitting time for the control group (approximately 45 minutes) should not alter pre-stressor baseline BP values. In Shvartz et al. (1983), there were no significant changes in heart rate, cardiac output, or SBP after *five* hours of uninterrupted sitting compared to initial baseline in a sample of eight young men. DBP did increase after five hours in this sample, however, the differences between baseline and one hour of sitting were non-significant. Perdomo and colleagues (2019), in a crossover trial of midlife adults, showed that there were no significant differences in SBP and DBP values

[7] It should be noted that these recovery times are somewhat longer than what is to be expected from the exercise physiology literature. This discrepancy could be due to the relatively sedentary lifestyle of the pilot participants as well as use of an older blood pressure monitor that had not been calibrated for some time. Further, more frequent BP reading intervals may have detected a more rapid BP recovery than observed here.

between 60 minutes of sitting and two moderate physical activity conditions (20 minutes of sitting followed by 10 minutes of walking and 30 minutes of walking). A design involving more prolonged sitting (e.g., two or more hours) may be problematic for this research question, but the relatively short sitting period in our study is not expected to systematically influence the pre-stressor BP baseline. Taken together, previous work and our pilot data suggest that there will not be systematic group differences in the pre-stressor BP baselines in this proposed project.

1.9.2 Should individuals across all levels of habitual physical activity be included in the sample?

The extent to which blood pressure responses to stress change following physical activity in more physically active individuals warrants consideration for the targeted population for the current investigation. One concern is that highly active individuals may exhibit different cardiovascular responses to laboratory stressors after a physical activity bout relative to their less active counterparts. However, prior work has not shown significant differences in BP responses based upon physical activity status. Directly comparing 80 highly active and inactive undergraduate participants, Roth (1989) did not observe differences in BP responses to stress following 20 minutes of moderate physical activity between these two groups. Likewise, our ambulatory study found that the moderating effect of recent physical activity on DBP responses to Task Strain was observed even when controlling for habitual physical activity. When habitual physical activity was analyzed here as part of a three-way interaction (Task Strain X weekly physical activity X recent physical activity), we did not see a significant moderating effect of habitual physical activity on the relationship between recent physical activity and DBP responses to Task Strain ($b = 0.11$, $p = 0.84$).

Though prior work does not suggest that activity status has an important bearing on BP responses to stress, it would be prudent to focus the efforts of the current investigation in a population that would maximize our ability to detect an effect from this physical activity manipulation. Additionally, a practical consideration here is that highly active individuals may respond to the physical activity conditions differently than their less active counterparts, such as not reaching the target HR within the allotted time. Thus, this sample will exclude subjects who are highly physically active. To operationalize this degree of physical activity, we use the national guidelines for minimum recommended amount of physical activity: 150 minutes of moderate physical activity per week, 75 minutes of vigorous activity, or equivalent combination of moderate- and vigorous-intensity physical activity (Piercy et al., 2018).

1.9.3 Limitations

Limitations of the current proposed investigation should be noted. First, we do not measure the underling physiological mechanisms that may account for reduced BPRS. Instead, we focus on the highest priority in this stage in the developing of this research question: establishing the effect of light physical activity on reduced BPRS in a well-designed study. Positive findings here would encourage future research to investigate these underlying physiological mechanisms.

Another limitation is that there may be individual differences in the recovery rate from physical activity. Our pilot data suggested that following light physical activity, 88.8% and 66.6% of the sample returned to within two mmHg of SBP and DBP averaged baseline values, respectively, by the 16-minute BP reading. Following moderate physical activity, these percentages were 70% and 60%. Two individuals did not return to SBP baseline while one other individual did not return to DBP baseline within the 30-minute protocol following the moderate physical activity condition. Though the pilot data generally supports a return to baseline values within 16 minutes, however, some individuals may not experience a return to baseline within the allotted recovery period. One strategy to address this concern would be to define the recovery period as the time necessary to return to a stable baseline for each individual. Thus, the recovery period duration would vary across individuals and groups. However, this strategy will not be adopted as it would introduce systematic differences within and between groups. Thus, the extent to which these few "non-recoverers" may influence the findings in this proposed project will be addressed in a post hoc sensitivity analysis.

1.10 Aims and Hypotheses

Aim 1: To test the effect of light physical activity bouts on attenuating blood pressure responses to psychosocial stressors in a laboratory design.

Hypothesis 1: Participants in the light physical activity group will show lower systolic and diastolic blood pressure responses to laboratory stressors following the activity bout compared to participants in the control group.

Aim 2: To test the effect of moderate physical activity bouts on attenuating blood pressure responses to psychosocial stressors in a laboratory design.

Hypothesis 2: Participants in the moderate physical activity group will show lower systolic and diastolic blood pressure responses to laboratory stressors compared participants in the control group.

Exploratory Aim: To compare the magnitude of effects of light and moderate physical activity bouts on attenuating blood pressure responses to psychosocial stressors following the activity periods.

2.0 Methods

2.1 Participants

Participants between the ages of 18-24 were recruited from two sources through the University of Pittsburgh. The primary recruitment source was through the University of Pittsburgh undergraduate subject pool, in which Introduction to Psychology students received course credit as compensation for participation in research studies. Participants received two hours of course credit as compensation for their involvement. The second recruitment source was through Pitt+Me, an online participant database funded through the University of Pittsburgh. Participants through Pitt+Me were compensated $15 for the completed visit to ensure a comparably motivated sample.

Exclusionary Criteria. Individuals with a history of cardiovascular disease (e.g., Krantz et al., 1991) and hypertension (e.g., Manuck et al., 1990) have been shown to have elevated cardiovascular responses to laboratory stressors relative to their healthy counterparts. Conversely, pregnant women have been shown to have diminished blood pressure responses to psychosocial stressors relative to their non-pregnant counterparts (Matthews & Rodin, 1992). Thus, we excluded individuals with a history of cardiovascular disease, Stage 2 hypertension (systolic/diastolic BP ≥ 160/100 mm Hg), use of any antihypertensive medications, or those who were pregnant. We also excluded participants who had an injury or physical disability that limited their walking on a treadmill or whose physical activity habits met national guidelines for the minimum recommended amount of physical activity as noted earlier. See Appendix A for screening questions.

2.2 Procedure Overview

Across both recruitment sources, interested study participants disclosed their contact information through the subject pool portal or through the Pitt+Me website. These potential participants were contacted via phone by the study investigator and screened for study eligibility (see Appendix A). Prior to the laboratory visit, participants were asked to abstain from vigorous physical activity, alcohol consumption, and non-prescription medications for 24 hours, as well as caffeine for 12 hours and tobacco products for 3 hours.

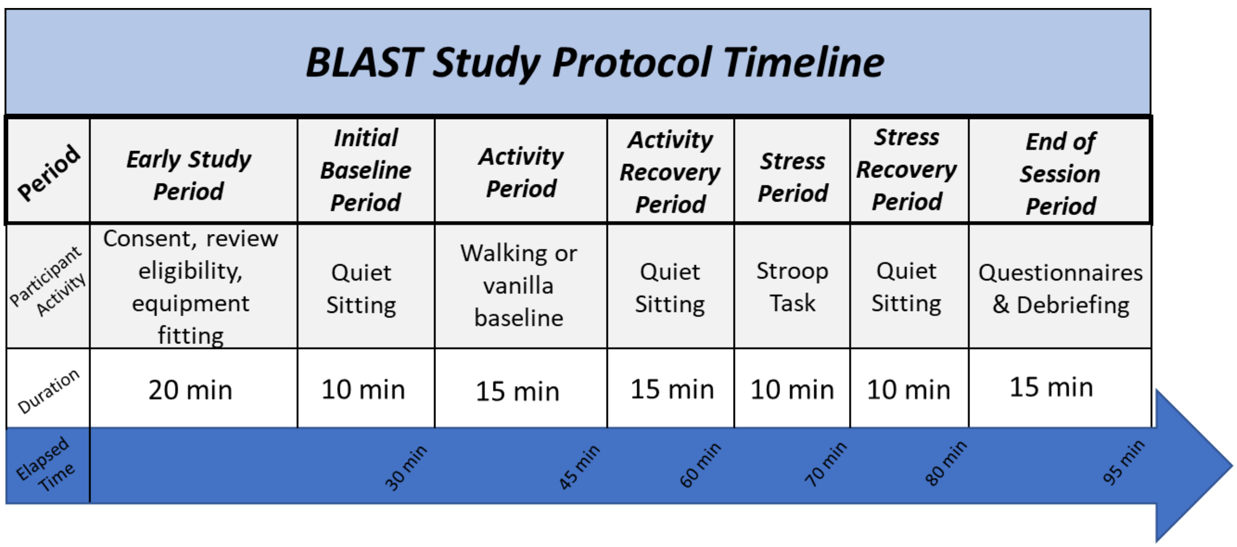

Figure 4. Schematic of Study Timeline

As depicted in Figure 4, the experimental session was divided into seven study periods. Upon arrival, the researcher verified study eligibility and obtained written informed consent during the first study period (“early study period”). Following informed consent, participants were instructed on how to wear the heart rate sensor followed by the measurement of height and weight. After participants put on the heart rate sensor in private, the researcher confirmed proper placement of the sensor with the participant. Participants were then measured and fitted for the properly fitted blood pressure cuff.

During the second period ("initial baseline period"), participants were instructed to sit quietly in a comfortable chair for a 10-minute period in order to establish a resting baseline. No reading materials were provided to the participants, and participants refrained from speaking and screen use. Blood pressure readings were taken at two-minute intervals (at 2, 4, 6, 8, and 10 minutes). The average of the last three readings were used to determine participant eligibility for resting blood pressure. Participants whose blood pressure exceeded the exclusionary criterion (systolic/diastolic BP $\geq$ 160/100 mm Hg) were dismissed.

Upon confirmation of study eligibility and following this initial baseline period, participants were randomly assigned to one of three groups: light physical activity, moderate physical activity, and control. During the third period ("activity period"), participants in the two physical activity groups were asked to engage in 15 consecutive minutes walking on a treadmill (NordicTrack, Logan, UT; Model T6.5S) in the same room[8] followed by a 30 second cool down period. Participants were supervised by a researcher from the adjacent room and through a one-way mirror during the physical activity bout to ensure safety of the participant as well as to titrate the treadmill settings as needed. Participants in the control condition engaged in 15 minutes of a "vanilla baseline" task in the same room (see below). Like the initial baseline period, no reading materials were provided, and participants were asked to refrain from speaking and cell phone use.

[8] In order to maximize the percentages of physical activity minutes in the intended heart rate range for each of these two conditions, there was no warm-up or extended cool-down period used in this protocol. This decision was also made to ensure that the moderate physical activity bout was not preceded or followed by light physical activity. For instance, a 3-minute warm-up and 2-minute cool-down could qualify as light physical activity. Instead, we used a higher starting speed in the moderate physical activity condition to ensure that the average HR percentage met our targeted HR range.

Following this 15-minute activity period, all participants underwent a fourth study period: a 15-minute "activity recovery period" (see Figure 4). Though our pilot data suggested that the light physical activity group might require a shorter recovery period to return to pre-activity BP values, we wanted to maintain an identical procedure across all conditions. Immediately following the conclusion of the activity recovery period, participants were administered Activation-Deactivation Adjective Check List (see below).

At the beginning of the stress period, participations received instructions on the Stroop Word-Color Interference Task and completed a brief (< 1 minute) practice trial period. Participants were then administered the Stroop task for 10 minutes (see details below). Blood pressure readings were taken at two-minute intervals during this period (at 0, 2, 4, 6, 8, and 10 minutes[9]). This stressor task was followed by the sixth study period: a 10-minute stress recovery period with blood pressure readings every two minutes (at 2, 4, 6, 8, and 10 minutes). To conclude their study involvement, participants then completed a demographics and health behavior form (see Appendix B), additional questionnaires (see below), and were debriefed on the experiment during the seventh study period. See Figure 4 for schematic of complete study procedure.

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[9] The original protocol involved readings starting at 2 minutes. In September 2020, upon observing unexpectedly low BP responses among the control participants, Dr. Kamarck and I agreed to add a reading at the start of the Stroop task (0 minutes) to maximize the likelihood of detecting heightened BP responses. Removing these early participants from later analyses did not appreciably alter the pattern of findings.

2.3 COVID-19 Mitigation Efforts

In order to conduct in-person data collection during the COVID-19 pandemic, this study had a comprehensive COVID-19 mitigation plan approved by the University dean's office. This mitigation plan involved steps to minimize health risks of COVID-19 consistent with public health best practice, University guidance, and government restrictions. The section below highlights steps within this mitigation plan that are pertinent to the interpretation of the data.

All study participants completed a health phone screen 24-48 hours prior to the visit. Questions centered on COVID-19 test results, symptoms, possible viral exposure, and out-of-state travel in the prior 14 days; participants who endorsed these items were rescheduled. Eligible participants completed a second health screen upon arrival to the building. If eligible after this second health screen, the researcher met the participant outside or in the building lobby and conducted a temperature check. Participants were provided a surgical mask to wear for the entire duration within the building. Researchers also wore a surgical mask for the duration of the visit and additionally donned a face shield for any interactions within six feet of the participant.

Upon arrival to the participant room, participants were informed of social distancing precautions and that communication with the participant would primarily occur from the hallway or through an intercom system. Few procedures (e.g., measurement of height and weight, blood pressure cuff fitting) occurred within six feet; most procedures (e.g., informed consent, eligibility verification, stressor task instructors) occurred via intercom. For participants randomized to the physical activity conditions, the researcher remotely titrated speed and/or grade of the treadmill from the control room using Bluetooth-enabled pistons and confirmed via a video monitor positioned above treadmill control panel. For these participants, ratings of perceived exertion (RPE's) were completed by pointing to a rating chart posted on the adjacent wall that was visible from the control room. These participants in the light and moderate physical activity groups were asked to remove their masks only during the physical activity bout as to avoid interference with respiration.

2.4 Measures

2.4.1 Physical Activity Intensity

Under the supervision of the research staff, participant exertion was modulated to remain within the prescribed light or moderate physical activity intensity range. Participants across both activity groups were informed that the treadmill would be adjusted appropriated to keep them within the prescribed physical activity range. Participants were also informed that the treadmill would be adjusted should they report the need to jog or run in order to maintain the treadmill pace. Participants in the light physical activity condition started on the treadmill at 2.0 mph (as previously described in Larsen et al., 2014). Participants in the moderate physical activity group were instructed to maintain a brisk walking pace. Pilot data collection suggested that shorter participants were challenged to sustain the brisk walking pace without jogging; thus, participants under 64 inches in the moderate physical activity condition started at 3.5 mph, whereas participants over 64 inches started at 3.8 mph.

Participant heart rate was closely monitored to ensure that exertion fell within the prescribed physical activity range: under 60 percent of maximal heart rate (HR_{max}) for the light physical activity group and within the range of 70-75% HR_{max} for the moderate physical activity group. These values were chosen to best distinguish the light physical activity bout from the moderate physical activity bout. Participants' heart rate was recorded in 1-minute epochs, and titration decisions were determined by the averaged HR from the prior two minutes. Speed and incline were moderated as necessary by the researcher to ensure that the participant exertion remained within the prescribed physical activity intensity range (see titration algorithms in Figures 5-7). HR_{max} was calculated by using the conventional formula[10]: $HR_{max} = 220 - \text{age}$. A Polar H10 heart rate monitor (Polar Electro, Finland), a heart rate sensor designed for use during physical activity, was affixed to the participant using a chest strap for real-time HR monitoring. For privacy reasons, participants were instructed on proper placement and were permitted to affix the device independently. The researcher remained available outside of the room to assist upon request, and placement of the Polar sensor was confirmed by the participant pointing their finger form over their clothes to the position of the device on their chest. Women had been instructed prior to the visit not to wear wire bras to avoid interference with the Polar device.

As a fidelity measure, Borg's rating of perceived exertion (RPE) was assessed every two minutes during the walking condition. The scale ranges from 6 (no exertion) to 20 (maximal exertion). Participants were oriented to the use of the RPE scale prior to the start of the physical activity bout.

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[10] For example, the target HR of an 18-year old participant assigned to the light physical activity group must not exceed 121 bpm, and the target HR range would be between 141 and 152 bpm for the same participant in the moderate physical activity group.

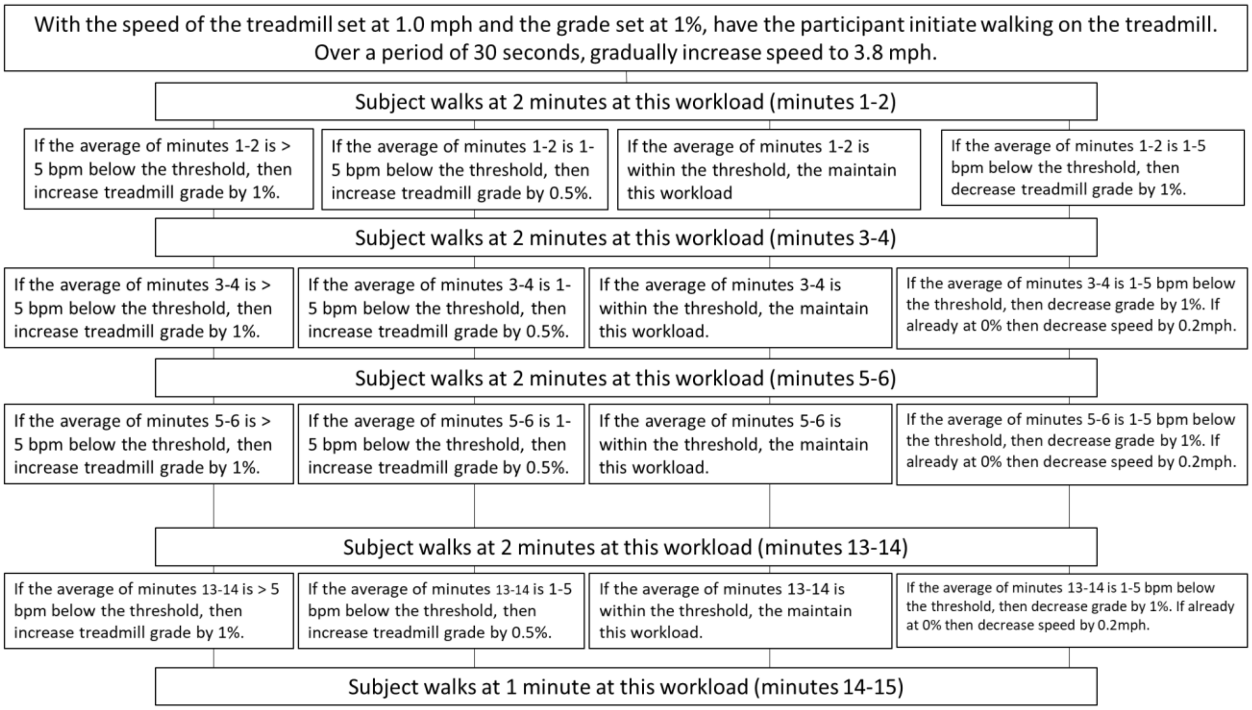

Figure 5. Algorithm I for Moderate Physical Activity Group

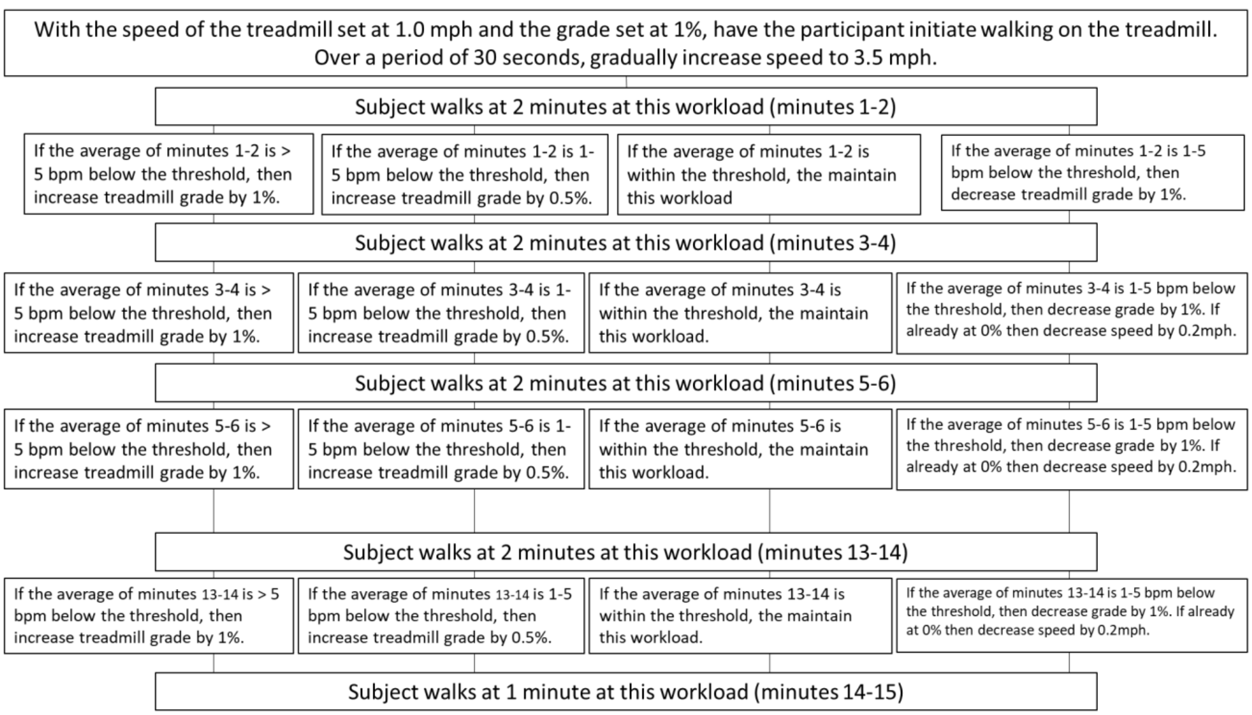

Figure 6. Algorithm II for Moderate Physical Activity Group

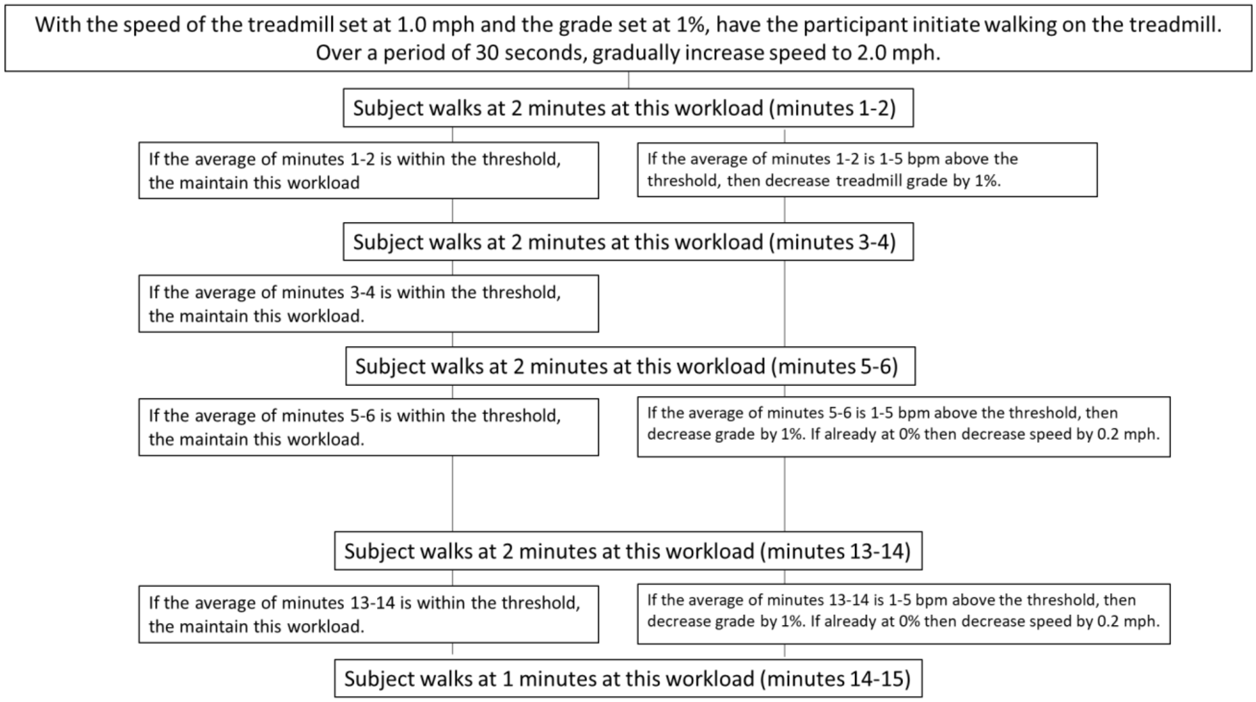

Figure 7. Algorithm for Light Physical Activity Group

2.4.2 Blood pressure

Systolic and diastolic blood pressure readings were measured using a Critikon Dinamap blood pressure monitor (Model 8100). This instrument allows for automatic inflation and deflation of a standard occluding cuff. Arm measurements were taken to select a properly fitted blood pressure cuff. The blood pressure cuff was attached to the subject’s left arm. Readings were taken in two-minute intervals during the baseline, stressor task, and stressor task recovery periods, and in three-minute intervals during the activity recovery period.

2.4.3 Vanilla Baseline Task

The vanilla baseline task is a minimally demanding color identification computerized task chosen to standardize attentional demands and participant behaviors during the resting baseline conditions. This task required participants to count the number of times a designated color (here, green) appeared on the screen. A new color appeared every 10 seconds. As 10 and 20 minute versions of the vanilla baseline task have been associated with acceptable, stable cardiovascular activity (Jennings et al., 1992), we reasoned that a 15 minute version would perform in the same manner.

2.4.4 Stressor Task

Participants underwent a computerized version of the Stroop Color-Word Interference Task, a well-known stressor task that has been shown in previous work to reliably evoke increases in blood pressure (e.g., Debski et al., 1991; Kamarck et al., 1992). During the Stroop task, participants were presented with a block of color words (e.g., blue, red) displayed in text color incongruent with each color word (e.g., the word “red” printed in blue ink instead of red ink) and were asked to identify the text color. To further enhance the stressfulness of this task, a disruptive, pre-recorded voice of an incorrect answer was loudly broadcasted once per trial during the task administration. Task difficulty was automatically titrated within task administration in order for participants to maintain a success rate of 60% in a manner consistent with previous work (e.g., Debski et al., 1991; Kamarck et al., 1992). Task duration was 10 minutes.

2.4.5 Questionnaires

In order to help us characterize the sample, the following five questionnaires were administered. See Appendices C-G for the questionnaires:

2.4.5.1 The Activation-Deactivation Adjective Check List (AD ACL).

The AD ACL is a 20-item self-administered questionnaire designed to measure momentary affective status (Thayer, 1990). In this questionnaire, participants rated their current feelings for 20 adjectives (e.g., energetic, calm, tired, tense) using a 4-point response scale ("definitely" to "definitely not"). The AD ACL produces four interdependent factors: Energy (energetic, lively, active, vigorous, full-of-pep), Tiredness (sleepy, drowsy, tired, wide-awake, and wakeful), Tension (tense, clutched-up, fearful, jittery, intense, still), and Calmness (still, at-rest, calm, quiet, place). The AD-ACL has been shown by factor analysis to support a two bipolar dimensions consisting of Energetic Arousal (Energy and Tiredness adjectives) and Tense Arousal (Tension and Calmness adjectives); each of the scales have been shown to be associated with high test-retest reliability when administered in immediate sequence (Thayer, 1978). For this work, we used the Energetic Arousal and Tense Arousal dimensions. Energetic Arousal was calculated as the sum of the Energy and Tiredness scales, and Tense Arousal was calculated as the sum of the Tension and Calmness scales.

2.4.5.2 Paffenbarger Physical Activity Questionnaire (Paffenbarger)

The Paffenbarger is a widely used self-administered questionnaire designed to measure weekly energy expenditure in adults (Paffenbarger Jr et al., 1978). In this questionnaire, participants were asked to report the number of city blocks they walk and flights of stairs climbed on a typical day, and the frequency and duration of any sports or recreational activities in the past week. Estimates of weekly kilocalorie expenditure were computed based upon their responses. The Paffenbarger questionnaire has been shown to have high test-retest reproducibility over a one-month period (Ainsworth et al., 1993) and adequate convergent validity with measures of maximal oxygen uptake (Nowak et al., 2010) and body mass index (Choo et al., 2010).

2.4.5.3 Sedentary Behavior Questionnaire (SBQ)

The SBQ is a 6-item self-administered questionnaire designed to measure estimates of the typical time spent in six non-work-related sedentary behaviors (watching television, computer use, doing paperwork, reading, phone use, travelling in a vehicle) on weekdays and on weekends on a scale consisting of nine responses (range: "none" to "six hours or more"). Weekday and weekend totals were weighted to provide an average of total sedentary time in hours per week. This questionnaire was adapted from a questionnaire used in the Coronary Artery Risk Development in Young Adults (CARDIA) Study, and previous work has shown adequate convergent validity with accelerometer-derived inactivity minutes, body mass index (BMI), and other questionnaire sitting time (ICC range: .51 - .93; Rosenberg et al., 2010). Items were further adapted for a college-aged population (see Appendix E).

2.4.5.4 Positive and Negative Affect Schedule (PANAS)

The PANAS is a common 20-item self-reported measure of trait positive and negative affect. In this questionnaire, participants are asked to rate a 20-item list of adjectives using a 5-point Likert scale ("very slight or not at all" to "all the time/extremely") indicating the degree to which they "generally feel this way." Ten items contribute to the positive affect scale (e.g. enthusiastic, excited, alert) and 10 to the negative affect scale (e.g. upset, afraid). Ratings were averaged to generate positive affect and negative affect scores. The PANAS has been shown to have good internal consistency (Cronbach's alpha reported at .87 and .86 for positive and negative affect scales, respectively) and acceptable 8-week test-retest reliability (r = .68 for positive affect and r = .71 for negative affect; Watson et al., 1988).

2.4.5.5 Perceived Stress Scale (PSS)

The PSS is one of the most widely used questionnaires to measure recent stress perception and is designed to be consistent with the cognitive appraisal model of stress (Cohen et al., 1983). This version of the scale involves 10 self-reported questionnaire items inquiring about global environmental demands and coping abilities during the past month. In the PSS, Participants rate each item on a Likert scale from 0 ("never") to 4 ("very often"). Internal consistency for this version of the PSS has ranged from .78 to .91 (Cohen & Janicki-Deverts, 2012), and it has shown acceptable test-retest reliability over short duration periods (Lee, 2012).

2.5 Analytic Plan

2.5.1 Data Reduction

For each participant, the initial baseline SBP and DBP values were computed as the mean of the last three SBP and DBP readings, respectively, obtained during the 10-minute initial baseline period. The activity recovery SBP and DBP values were calculated as the mean of the last two SBP and DBP readings, respectively, during the activity recovery period. For the Stroop task, SBP and DBP responses were calculated as the mean of the six SBP and DBP readings obtained during the stress period, respectively. Thus, each period produced one value for each BP parameter.

2.5.2 Covariate Determination

A series of one-way ANOVA analyses were performed to assess group differences in the following demographic and baseline characteristics: sex, age, race, BMI, habitual physical activity, and initial baseline SBP and DBP. Each of these variables were specified as the dependent variable in separate analyses. Significant results were followed by post hoc testing to determine which of the two physical activity groups was different from the control group, and whether the physical activity groups differed from one another. We did not anticipate group differences in these characteristics due to random assignment to each condition; significant group differences for these factors were entered as covariates in the models outlined below.

2.5.3 Analyses

All hypotheses were tested in a series of repeated measures multivariate analysis of variance (MANOVA) models using SAS (version 9.4). A MANOVA model is preferred to reduce the number of analyses and subsequent risk for Type I error. First, an omnibus 3 x 2 MANOVA was performed with Group (control, light physical activity, moderate physical activity) as the between-subject factor and Period (activity recovery period, stress period) as the repeated within-subject factor. In cases where significant Group x Period interactions were observed, separate analyses were performed for SBP and DBP as the outcome variables. As noted earlier, post hoc sensitivity analyses were performed excluding any participants who failed to return to their initial baseline BP values within the 15-minute activity recovery period. Here, we removed these participants and performed the same analyses described above.

The procedure involving the Group by Period MANOVA and applicable post hoc analyses for BP outcome variables and "non-recoverers" described above was repeated to test Hypotheses 1 and 2 and the Exploratory Aim. For the Hypothesis 1 analysis, the between-subject factor for the post hoc analysis involved only the control and light physical activity groups. For the Hypothesis 2 analysis, the between-subject factor for the post hoc analyses involved only the control and moderate physical activity groups. For the Exploratory Aim, the Group between-subject factor involved only the control and moderate physical activity groups.

A final set of analyses controlled for the potentially confounding effect of elevated baseline blood pressure on exaggerated blood pressure responding. In this model, change scores (BP during Stroop task – BP during baseline) were treated as dependent measures with baseline BP as a covariate. Following the procedure outlined above, applicable post hoc analyses testing the main hypotheses and removing "non-recoverers" was performed.

2.5.4 Power Analysis

Power analyses were conducted using G*Power Version 3.1 (Faul et al., 2009). The first power analysis established the estimated sample size for comparison between the light physical activity and control groups (Aim 1). No study to the author's knowledge has examined the association between light physical activity and BP responses to stress. For this power analysis, we assumed a small-to-medium effect size ($f = .25$). Using this effect size, α of 0.05, a power of .80 and two measurement periods (baseline and stress task periods) using a between-within subjects MANOVA, this power analysis generated a recommended sample size of 64 participants per group to detect an effect of light physical activity on BP responses to stress in the proposed study. Thus, we aimed to recruit a sample of 192 participants in order to have an adequately powered three-group design (control, light physical activity, and moderate physical activity).

This power analysis takes a conservative approach for the analysis involving the moderate physical activity group. The estimated effect size involving the moderate physical activity group has been shown to be larger (e.g., f = .30 shown in Taylor & Katomeri, 2006) than the effect size that was adopted for the light physical activity condition. Use of the larger effect size resulted in a smaller required sample size for comparisons between the moderate physical activity and control groups than for the light physical activity and control groups. However, we prioritized the above power analysis in order to have an equal number of participants across the three groups. With a sample size of 192 participants, we estimated that we would have sufficient power to detect the omnibus comparison (power of .88) and comparisons between the moderate physical activity group and the control group (power of .98)

Note that this sample size of 192 participants is powered for comparisons between either physical activity group and the control group (Aims 1 and 2). The study was not powered to detect group differences between the two physical activity groups outlined in Exploratory Aim. As the primary question of the current investigation involved the analyses for Aim 1, we recruited a sample that was powered for that analysis. Notwithstanding, the comparison between the two physical activity groups may be underpowered and should be interpreted with caution.

3.0 Results

3.1 Sample Characteristics

Participants were recruited from September to November 2020 and from January to April 2021. As shown in Figure 8, 459 individuals were screened for eligibility. The eligibility rate for the sample was 53.4%[11], with virtually all excluded individuals meeting national guidelines for the minimum recommended amount of physical activity. No participants were dismissed for exceeding the high blood pressure exclusionary criterion. A total of 183 participants were randomized to one of the three experimental conditions. Between the two recruitment sources, 148 completers were from the subject pool (80.9%) and 35 completers were from Pitt+Me (19.1%). Of these 183 participants[12], one participant was removed due to a blood pressure cuff malfunction during the session[13], and three participants were removed after data collection due to disclosing

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[11] There did not appear to be gender differences in eligibility. We screened 163 males (35.5%) and 294 females (61.1%), which is nearly identical to the gender composition of the completed sample. Eligibility rates did vary somewhat by semester. The eligibility rate for the fall term (September to November 2020) was 50.8%, whereas in the spring term (January to April 2021) eligibility rate was 58.4%. This difference in eligibility rate is likely due to seasonal variation in physical activity habits.

[12] The recruited sample was 9 participants below the targeted sample size of 192. Recruitment ended early due to the PI adhering to COVID-19 quarantine guidelines in place at that time. We do not believe that 9 additional individuals (or approximately 3 per experimental group) would have altered the pattern of findings reported later.

[13] There was a small puncture in the hose that was not detected until after the visit. No BP data were obtained during the stress period and stress recovery period. We considered an intent-to-treat analysis with imputation of the missing

use of spironolactone, a diuretic used by these participants to treat acne, during review of their medical history. Three of these participants were in the light physical activity group, and one participant was in the moderate physical activity group. The final sample consisted of 179 individuals: 60 participants in the control group, 59 participants in the light physical activity group, and 60 participants in the moderate physical activity group. See Table 2 for participant demographics for the entire sample and by group.

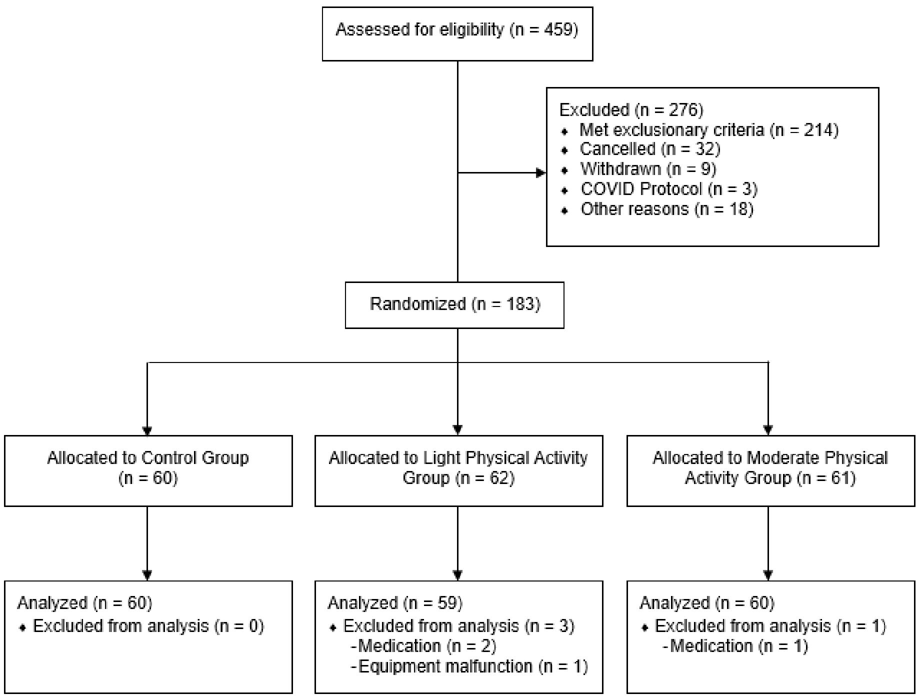

Figure 8. Study Recruitment

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data, but we opted to remove this person from analyses instead because from the pattern of our findings we inferred that there was a high likelihood that the results would not be altered with intent-to-treat analyses in this case. We also decided to remove this person entirely from analyses so that data-driven decisions (e.g., establishing demographic covariates) involved only those participants who had complete data.

Table 2. Participant Characteristics by Sample and Group

Participant Characteristics by Sample and Group

	Entire Sample (N = 179)	*Control Group (n = 60)*	*Light PA Group (n = 59)*	*Moderate PA Group (n = 60)*
Demographics	Mean (SD) or N (%)	Mean (SD) or N (%)	Mean (SD) or N (%)	Mean (SD) or N (%)
Biological Sex (% female)	65.4%	65.0%	64.4%	66.7%
Age (years)	19.32 (1.6)	19.21 (1.4)	19.34 (1.7)	19.42 (1.5)
Race				
White/Caucasian	113 (63.1%)	38 (63.3%)	30 (50.8%)	45 (75.0%)
Black/African American	11 (6.1%)	3 (5.0%)	4 (6.8%)	4 (6.7%)
Asian/Asian American	37 (20.7%)	8 (13.3%)	20 (33.9%)	9 (15.0%)
Hispanic/Latino	8 (4.5%)	4 (6.7%)	4 (6.8%)	0 (0.0%)
Mixed Ethnicity	9 (5.0%)	7 (11.7%)	1 (1.7%)	1 (1.7%)
Other	1 (0.6%)	0 (0.0%)	0 (0.0%)	1 (1.7%)
Body Mass Index	23.1 (4.4)	22.9 (5.2)	23.2 (3.7)	23.3 (4.2)
Habitual Physical Activity (estimated kilocalories)	1284.79 (1155.6)	1206.15 (1068.9)	1473.90 (1445.0)	1176.15 (881.2)
Perceived Stress Scale Score	16.5 (6.8)	16.9 (7.6)	15.8 (6.3)	16.8 (6.5)
PANAS - Positive Affect Score	32.2 (6.2)	32.9 (5.9)	31.4 (6.6)	32.4 (6.3)
PANAS - Negative Affect Score	20.0 (6.2)	20.5 (6.8)	19.0 (5.8)	20.6 (5.9)
Sedentary Behavior Questionnaire Total Score	58.1 (26.4)	56.6 (24.1)	59.9 (29.9)	58.0 (25.2)

Note. SD = Standard Deviation. PANAS = Positive and Negative Affect Schedule.

A series of one-way ANOVA analyses indicated that there were no group differences in sex (F (2, 176) = 0.04, p = .96), age (F (2, 176, = 0.24, p = .78), BMI (F (2, 176) = 0.13, p = .88), habitual physical activity levels (F (2, 175) = 1.19, p = .30), baseline SBP (F (2, 176 = 0.07, p = .93) or baseline DBP (F (2, 176) = 0.89, p = .41) values. The ANOVA models did suggest group differences in racial composition (F = (2, 176) = 3.11, p = .0472). To follow-up to these analyses, we categorized race as a dichotomous variable (White = 0, non-White = 1) and used a series of chi-squares to probe for unbalanced groups. Here, we found significant differences in racial composition between the light and moderate physical activity groups (χ^2 (1, N = 199) = 7.44, p = .006) such that there was a significantly higher proportion of Whites in the moderate physical activity group than in the light physical activity group. There were no significant racial composition differences between the control group and the light physical activity (χ^2 (1, N = 119) = 1.89, p = .17) or moderate physical activity (χ^2 (1, N = 120) = 1.91, p = .17) groups. Accordingly, race (White vs non-White) was entered into the models as a covariate[14].

3.2 Descriptive Statistics

Table 3 reports the mean cardiovascular activity for each study period involving blood pressure (initial baseline, activity recovery, stress, and stress recovery) for the entire sample and by group, and Figure 9 depicts the mean cardiovascular activity for these study periods for each group. Table 4 reports the aforementioned information after removing non-recoverers from the sample. Across these tables and figure, BP responses to the Stroop task appear to be most pronounced for the light physical activity group compared to the other groups, especially for SBP responses. Table 5 shows that SBP and DBP responses were modestly correlated (r = .60, $p < .0001$).

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[14] We also performed analyzes in which the race covariate was operationalized as Asian vs. non-Asian. Use of this race covariate did not alter the pattern of key findings reported later (e.g., omnibus MANOVA, repeated measures ANOVA comparing the light physical activity and control groups on SBP responses).

Table 3. Mean (SD) Cardiovascular Activity at Study Period

Table 3.
Mean (SD) Cardiovascular Activity at Study Period

		Entire Sample (N = 179)	*Control Group (n = 60)*	*Light PA Group (n = 59)*	*Moderate PA Group (n = 60)*
Variable		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Initial Baseline Period					
	SBP	111.7 (8.8)	111.4 (8.3)	111.8 (9.9)	112.0 (8.3)
	DBP	62.0 (7.2)	62.7 (8.5)	61.0 (6.9)	62.2 (6.2)
Activity Recovery Period					
	SBP	110.1 (8.9)	109.5 (8.3)	108.9 (8.8)	111.9 (9.5)
	DBP	60.4 (7.4)	60.6 (8.8)	59.0 (6.5)	61.6 (6.5)
Stress Period					
	SBP	112.4 (8.8)	110.7 (8.6)	112.9 (9.2)	113.6 (8.5)
	DBP	63.4 (7.4)	63.1 (8.4)	62.6 (6.9)	64.5 (6.7)
Stress Recovery Period					
	SBP	109.7 (8.4)	109.7 (8.5)	109.3 (8.4)	110.1 (8.3)
	DBP	61.2 (7.6)	62.2 (8.7)	59.8 (7.1)	61.5 (7.0)
BP Responses to Stress					
	SBP	2.28 (6.0)	1.11 (5.0)	3.92 (5.8)	1.72 (6.84)
	DBP	2.98 (5.1)	2.50 (5.7)	3.58 (4.4)	2.87 (5.0)

Note. SD = Standard Deviation. BP = Blood Pressure. SBP = Systolic Blood Pressure. DBP = Diastolic Blood Pressure. BP Responses to stress were calculated as the arithmetic difference in averaged values during the final two readings of the activity recovery period and the entire Stroop task.

Table 4. Mean (SD) Cardiovascular Activity at Study Period - After Removing Non-Recoverers

Table 4.

Mean (SD) Cardiovascular Activity at Study Period - After Removing Non-Recoverers

		Entire Sample (N = 179)	*Control Group (n = 56)*	*Light PA Group (n = 53)*	*Moderate PA Group (n = 53)*
Variable		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Initial Baseline Period					
	SBP	111.8 (9.0)	111.1 (8.4)	112.0 (10.4)	112.1 (8.4)
	DBP	62.5 (7.2)	63.0 (8.5)	61.4 (7.0)	63.1 (5.8)
Activity Recovery Period					
	SBP	109.7 (9.1)	109.2 (8.5)	108.2 (8.9)	111.7 (9.7)
	DBP	60.0 (7.4)	60.2 (8.8)	59.0 (6.5)	61.3 (6.6)
Stress Period					
	SBP	112.3 (9.0)	110.8 (8.9)	112.6 (9.3)	113.5 (8.8)
	DBP	63.4 (7.5)	63.1 (8.3)	62.6 (7.1)	64.5 (6.9)
Stress Recovery Period					
	SBP	109.4 (8.4)	109.6 (8.8)	108.6 (8.1)	109.9 (8.3)
	DBP	61.2 (7.8)	62.2 (8.7)	59.5 (7.3)	61.6 (7.1)
BP Responses to Stress					
	SBP	2.55 (6.0)	1.58 (4.9)	4.31 (5.9)	1.83 (6.9)
	DBP	3.44 (4.9)	2.9 (5.6)	4.25 (4.1)	3.19 (5.0)

Note. SD = Standard Deviation. BP = Blood Pressure. SBP = Systolic Blood Pressure. DBP = Diastolic Blood Pressure. BP Responses to stress were calculated as the arithmetic difference in averaged values during the final two readings of the activity recovery period and the entire Stroop task.

Table 5. Pearson Correlation of Cardiovascular Responses during the Stress Period

Table 5.

Pearson Correlation of Cardiovascular Responses during the Stress Period

Variable	*1*	*2*	*3*	*4*	*5*
1. SBP Responses	-				
2. DBP Responses	.60***	-			
3. MAP Responses	.63***	.66***	-		
4. HR Dinamap Responses	.38***	.26**	.37***	-	
5. HR Polar Responses	.23**	.06	.15*	.64***	-

Note. ***p < .0001 ** p < .01* p < .05

SBP = Systolic Blood Pressure. DBP = Diastolic Blood Pressure.

MAP = Mean Arterial Pressure. HR = Heart Rate.

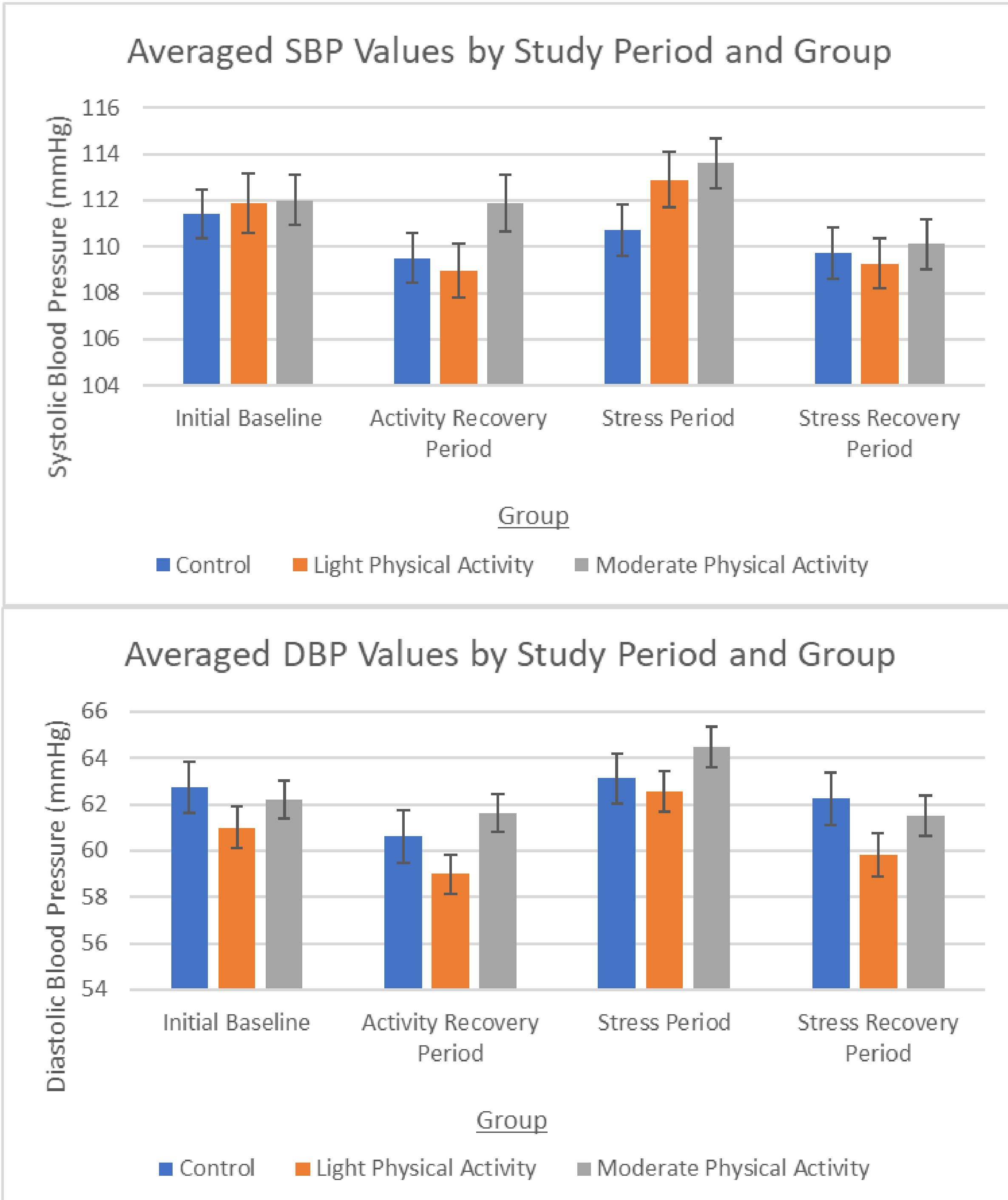


Figure 9. Blood Pressure Values by Study Period and Group

3.3 Manipulation Checks

3.3.1 Physical Activity Bout Manipulation

The average speed and grade for the light physical activity group was 1.94 mph and 0.83% grade. The average intensity for the light physical activity group was 53.0% HR_{max} (SD = 6.3%) and RPE of 8.4 (SD = 1.2). Both indices are considered to be in the "very light" intensity range according to the ACM. The average speed and grade for the moderate physical activity group was 3.54 mph and 1.76% grade. The average intensity for the moderate physical activity group was 71.3% HR_{max} (SD = 5.3%) and RPE of 12.4 (SD = 1.8). Both indices are considered to be in the "moderate" intensity range according to the ACM. These data suggest that the prescribed physical activity manipulations (<60% HR_{max} for the light physical activity group and 70-75% HR_{max} for the moderate physical activity group) were successful for the two physical activity groups.

3.3.2 BP Recovery from Physical Activity Bout

To determine the extent to which participant BP levels returned to pre-physical activity levels during the activity recovery period, a series of paired *t*-tests compared initial BP values with the BP values at the end of the activity recovery period. The moderate group did not significantly differ in SBP (t (59) = 0.14, p = .89) or DBP (t (59) = 0.84, p = .40) values during these two periods. However, the light physical activity group did show a significant reduction in SBP: (M = 2.89 [95% CI: 1.46 – 4.66]; t (58) = 4.04, p = .0002) and DBP (M = 2.02 [95% CI: 0.71 – 4.25]; t (58) = 3.08, p = .003) during the recovery period relative to the initial baseline period. Interestingly, the control group also showed a significant reduction in SBP: (M = 1.91 [95% CI: 0.43 – 4.88]; t

(59) = 2.58, p = .0125) and DBP (M = 2.11 [95% CI: 0.82 – 4.22]; t (59) = 3.28, p = .0017) values during the recovery period.

Per the planned analyses, participants who did not return to pre-activity baseline were removed in follow-up analyses. There is no established convention to define BP recovery following a baseline task. We reasoned that recovery values one standard deviation above the recovery values in the control group would best reflect a lack of recovery in the sample that cannot be attributed solely to measurement error. By this definition, seven individuals in the moderate group (11.6%), six individuals in the light group (10.2%), and four in the control group (6.67%) did not return to their initial baseline values. These non-recovering individuals were removed from analyses where specified. A series of one-way ANOVA analyses indicated that there were no group differences in sex (F (1, 177) = 0.22, p = .63), age (F (1, 177, = 0.16, p = .69), race (F = (1, 177) = 0.45, p = .50), BMI (F (1, 177) = 0.05, p = .82), habitual physical activity levels (F (1, 176) = 0.01, p = .93), or baseline SBP values (F (1, 177 = 0.14, p = .71) between the recovering and non-recovering individuals. The ANOVA models did suggest group differences in baseline DBP values (F = (1, 177) = 8.21, p = .0047), such that non-recoverers had significantly lower baseline DBP values than recoverers.

3.3.3 BP Responses to the Stroop Task

A series of paired t-tests compared SBP and DBP during the activity recovery to the stress period to determine whether BP levels were significantly elevated during the Stroop task. For the entire sample, paired t-tests show that both SBP (t (178) = 5.08, p < .0001) and DBP (t (178) = 7.83, p < .001) values significantly increased during the Stroop task by 2.28 mmHg and 2.97

mmHg, respectively. These data suggest that blood pressure increased during the stress period as expected, although the magnitude of effect was quite modest.

3.4 Main Analyses

3.4.1 Omnibus MANOVA Models

A repeated measures MANOVA compared group differences in SBP and DBP levels during the activity recovery period and the Stroop task period. The model involved two within-person factors and one between-person factor: Measure (2 levels: SBP and DBP), Period (2 levels: activity recovery period and stress period), and Group (3 levels: control, light physical activity, moderate physical activity). As explained earlier on page 42, all models covaried for race (White vs non-White).

This omnibus MANOVA revealed a significant Period effect (F (2, 174) = 8991.20, p < .0001) and a marginally significant Period by Group effect (F (4, 350) = 2.13, p = .077). Per the planned analyses, analyses were conducted again without individuals who failed to return to their initial baseline BP values ("non-recoverers"). This repeated measures MANOVA again revealed a significant Period effect (F (2, 157) = 7740.79, p < .0001) and a marginally significant Period by Group effect (F (4, 316) = 2.31, p = .058). These data collectively suggest marginally significant group differences in BP responses to stress irrespective of recovery status.

3.4.2 MANOVA Models by Group

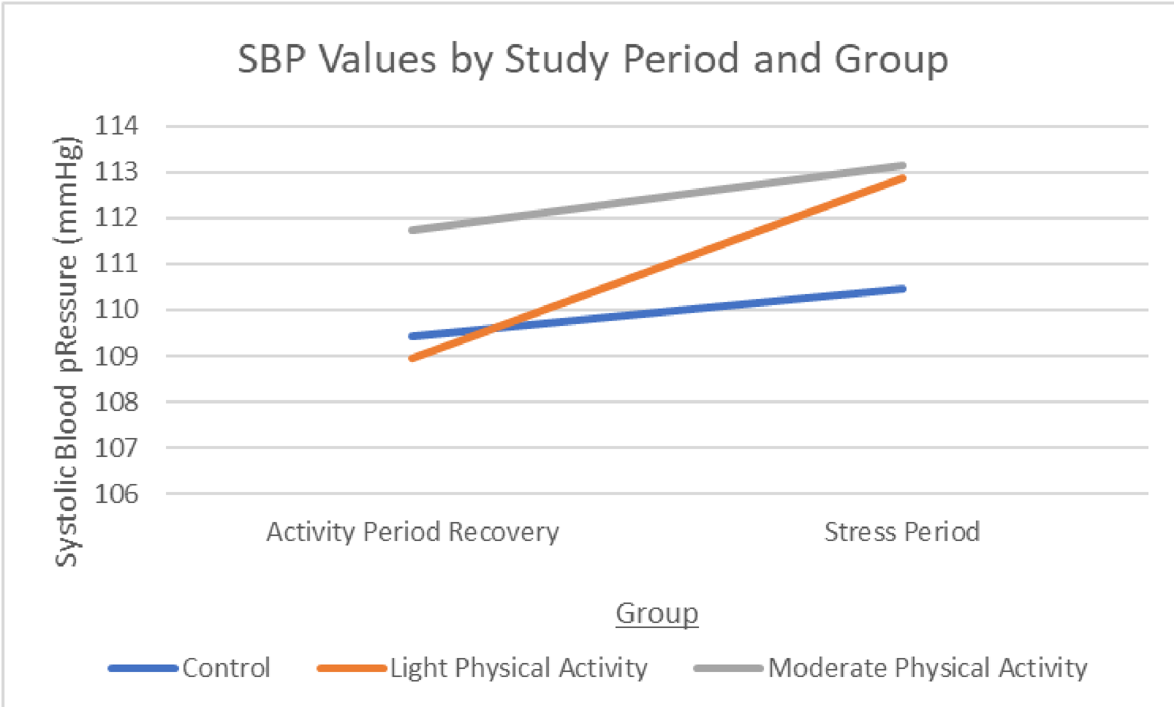
To probe which groups may account for the aforementioned effects, a series of three repeated measures MANOVA models compared the effects on BP between the light physical activity versus control groups (Hypothesis 1), the moderate physical activity versus control groups (Hypothesis 2), and the light physical activity versus moderate physical activity groups (Exploratory Hypothesis). Here, all MANOVA models found significant differences between the activity period and stress period (p's < .0001). Notably, we found a marginally significant Period by Group effect in models comparing light physical activity to controls (F (2, 115) = 2.37, p = .09) and the two physical activity groups (F (2, 115) = 2.71, p = .07). There was no significant Period by Group interaction in the comparison between moderate physical activity and controls (F (2, 116) = 1.44, p = .24). Contrary to Hypothesis 1 and Hypothesis 2, the MANOVA models featuring the entire sample failed to show significant group differences in BP responses.

Analyses were conducted again after removing non-recoverers. Consistent with the above analyses, we found a marginally significant Period by Group effect in models comparing light the physical activity group to the control group (F (2, 105) = 2.65, p = .07), and no significant interaction between the moderate physical activity group and the control group (F (2, 105) = 1.14, p = .32). However, a significant difference emerged between the two physical activity groups (F (2, 102) = 3.43, p = .036). Unlike the omnibus MANOVA, these MANOVA models involving these group comparisons suggests that removing non-recoverers from analyses was associated with significant differences in BP responses between the two physical activity groups.

3.4.3 ANOVA Models by Group and BP Outcome

The analytic plan proposed testing univariate models only if there were significant multivariate effects. The multivariate models reported above found significant differences in BP responses only between the two physical activity groups after removing non-recoverers, whereas only a marginally significant multivariate effect emerged for between light physical activity and control groups. Though this latter multivariate model did not reach the conventional threshold of statistical significance at $p < .05$, the marginally significant effect here could indicate that a significant effect involving one BP parameter is masked by a non-significant effect for the other BP parameter. Accordingly, we proceeded to test univariate models that separated SBP and DBP as the outcome variables for models addressing Hypothesis 1 (light physical activity vs. control groups) and the Exploratory Hypothesis (light physical activity vs moderate physical activity groups).

Unlike the multivariate model, the univariate follow-up analyses found that there was a significant Period by Group effect comparing light physical activity and control groups for SBP response (F (1, 116) = 7.64, p = .006) but not DBP response (F (1, 116) = 1.07, p = .30). However, these univariate models showed that SBP responses were significantly *larger* in the light physical activity group than both the control and moderate groups (see Figure 10). Even after removing non-recoverers analyses continued to show larger SBP responses among individuals in the light physical activity group compared to individuals in the control (F (1, 106) = 6.88, p = .01) and moderate physical activity (F (1, 103) = 5.47, p = .02) groups. Contrary to our main hypothesis, light physical activity participants showed SBP responses in the *opposite* direction than expected.



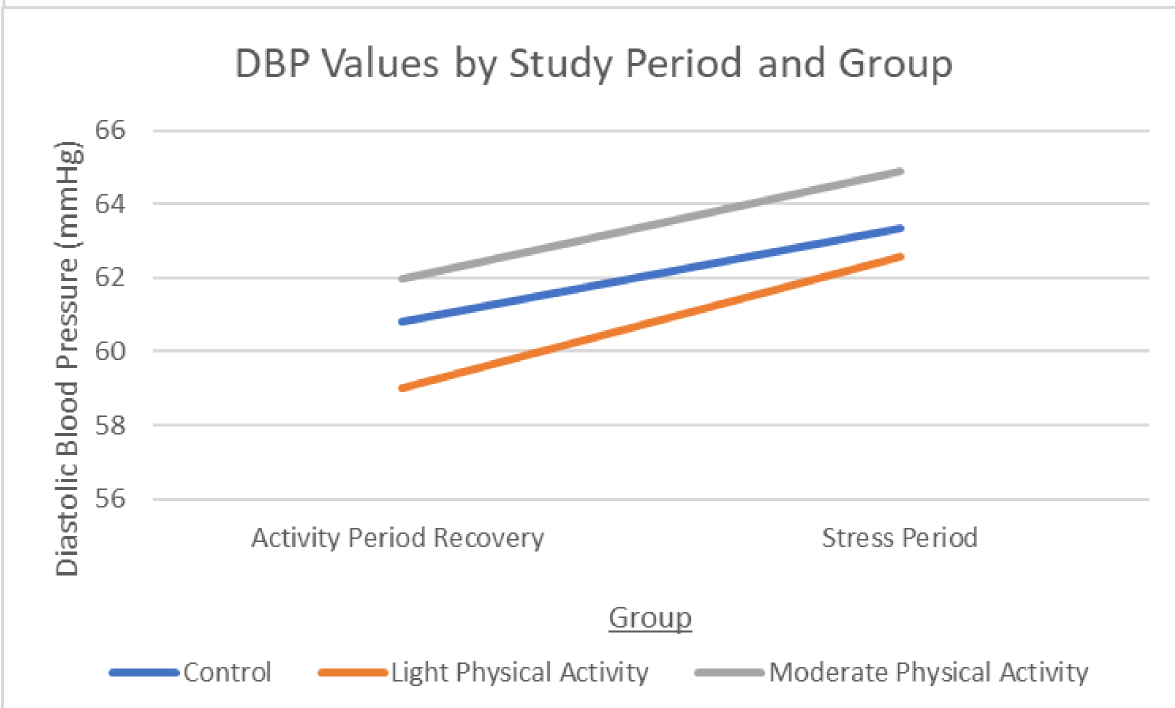


Figure 10. Blood pressure Values by Study Period and Group (Simplified)

In the univariate models for the Exploratory Hypothesis, the analyses showed a significant Period by Group interaction between the two physical activity groups for SBP (F (1, 116) = 5.41, p = .02) but not for DBP (F (1, 116) = 0.79, p = .37). This pattern of findings persisted after removing non-recoverers (SBP: F (1, 103) = 5.47, p = .02; DBP: F (1, 103) = 1.56, p = .21). Consistent with the unexpected findings for Hypothesis 1, SBP responses were higher in the light physical activity group than in the moderate physical activity group. Taken together, these data suggest that SBP responses to the Stroop task were significantly higher in the light physical activity group relative to the control and moderate physical activity groups.

3.4.4 ANCOVA Models

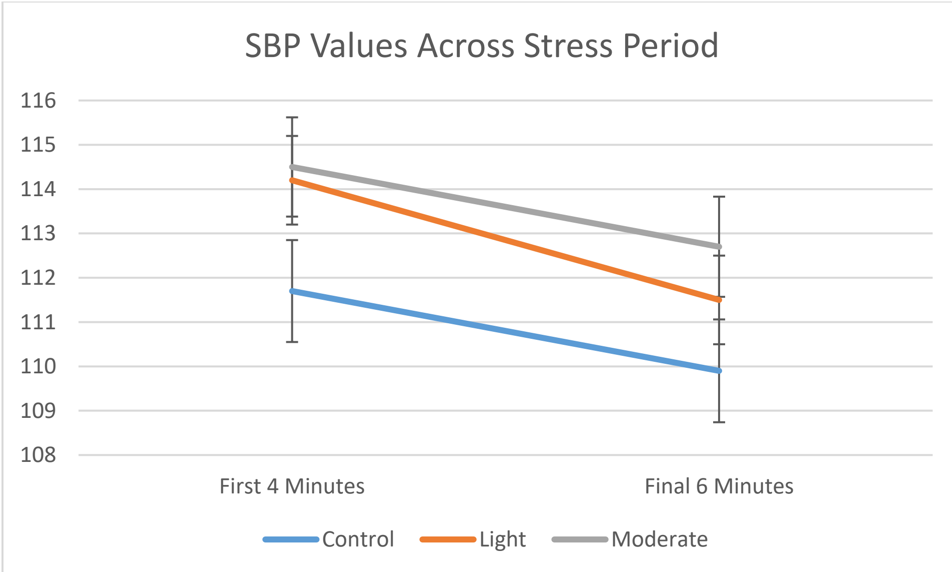
In a similar fashion, we conducted a series of ANCOVA models by controlling for initial baseline BP values. Omnibus ANCOVA models found significant group differences in SBP (F (2, 174) = 4.05, p = .019) but not DBP (F (2, 174) = 0.75, p = .47) responses. Consistent with the ANOVA models, follow-up ANCOVA analyses showed that the light physical activity group had larger SBP responses to the Stroop task compared to the control group (F (1, 115) = 7.47, p = .007) as well as the moderate physical activity group (F (1, 115) = 5.79, p = .018). There were no significant differences in DBP responses of the light physical activity group compared to the control (F (1, 115) = 1.15, p = .28) or moderate physical activity group DBP (F (1, 115) = 1.20, p = .27). There were no differences between SBP (F (1, 116) = 0.12, p = .73) or DBP responses (F (1, 116) = 0.13, p = .72) between the moderate physical activity group and controls. After removing non-recoverers from the analyses, we found that the higher SBP responses to the Stroop task in the light physical activity group persisted compared to the control (F (1, 105) = 6.69, p = .011) and the moderate physical activity groups (F (1, 102) = 5.83, p = .017). No significant differences emerged for the other comparisons. These findings, like the repeated measures models above, continue to suggest that the light physical activity group had higher SBP responses relative to both the controls and moderate physical activity groups. No significant group differences emerged for DBP responses.

3.5 Additional Exploratory Analyses

We conducted a series of additional exploratory analyses with two aims: to understand factors that may have contributed to the main findings, and to explore how physical activity may influence other indicators of cardiovascular responses to stress that were collected in this study. To address the first aim, we analyzed group differences across a variety of data collected in the current study that could explain our unexpected findings: BP habituation during the Stroop task, engagement with the Stroop, momentary affect, and potential behavioral and demographic moderators. The operationalization of these variables and analytic approaches are described in their respective sections below. In regards to the second aim, we conducted a series of ANCOVA models to understand if non-significant group differences emerged with respect to mean arterial pressure (MAP), the average pressure in the arteries during on cardiac cycle, and heart rate (HR) responses to stress. We also explored if there were group differences in the extent to which BP recovered from the Stroop task.

3.5.1 Within-task BP habituation

In response to anecdotal observations by the research staff during participant sessions that BP values were higher in the first half of the stress period than in the second half, we explored the possibility that blood pressure responses to the Stroop varied across the task. This analysis is important to assess whether group differences in BPRS were observed early in the stress period but simply masked by low responses later in the stress period. Figure 11 illustrates an observed downward trend in BP responses throughout the 10-minute Stroop task for each of the three groups. To analyze this trend, we compared the first three readings (at 0, 2, and 4 minutes) against the last three readings (at 6, 8, and 10 minutes). For the entire sample, paired *t*-tests show that both SBP (t (178) = 5.77, p < .0001) and DBP (t (178) = 6.75, p < .001) values were significantly higher in the first four minutes than in the last six minutes by 2.12 mmHg and 2.00 mmHg, respectively. In addition to sample-level analyses, group-level analyses also support elevations in BP during the first four minutes of the Stroop task than for the last six minutes across all three groups (all *p*'s <.01; see Figure 12). Group-level change score BP responses to stress were as follows: control (SBP: 2.23 mmHg; DBP: 3.08 mmHg), light physical activity (SBP: 5.26 mmHg; DBP: 4.67 mmHg), and moderate physical activity (SBP: 2.64 mmHg; DBP: 4.21 mmHg) groups. Despite performance titration programmed into the Stroop task, there is evidence of within-task BP habituation to the Stroop task.



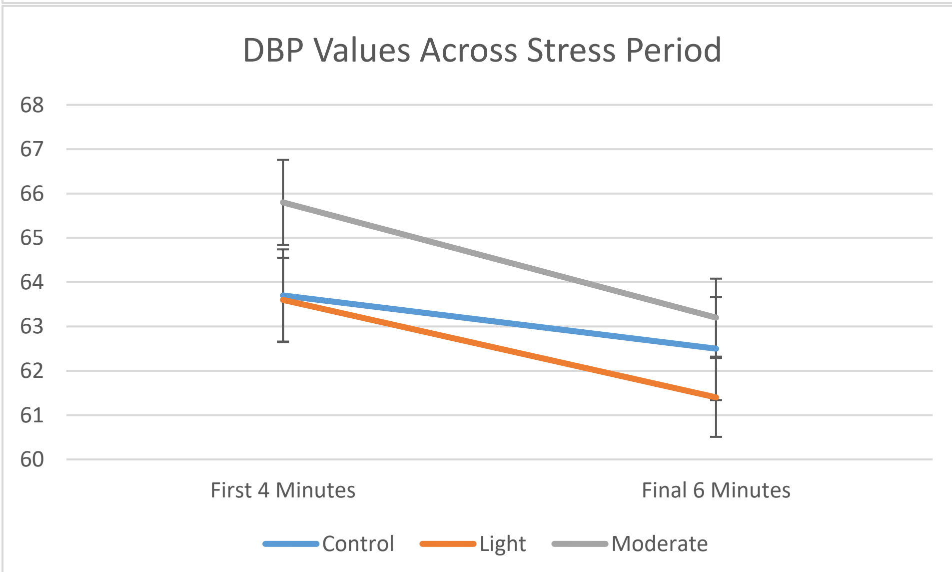
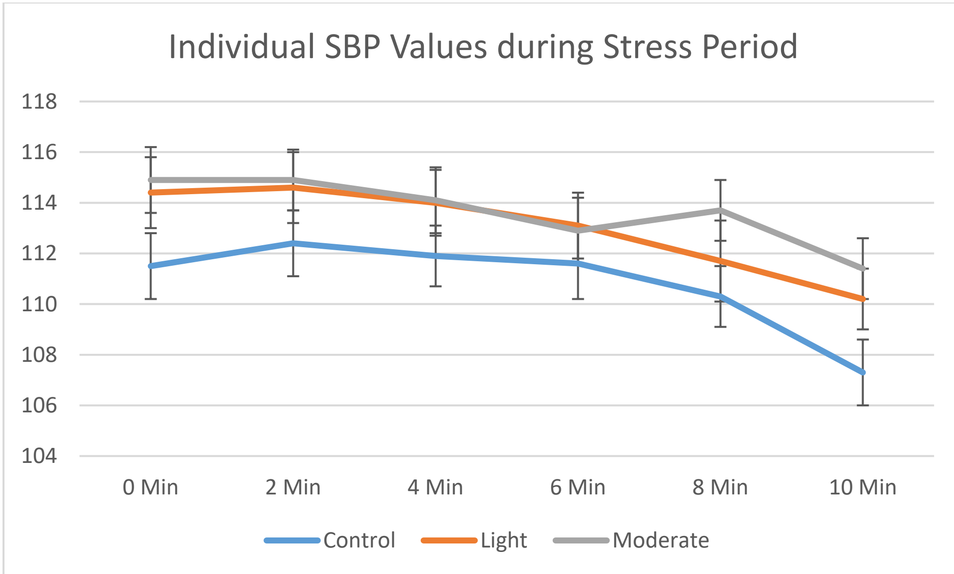


Figure 11. BP Values Across Stress Period



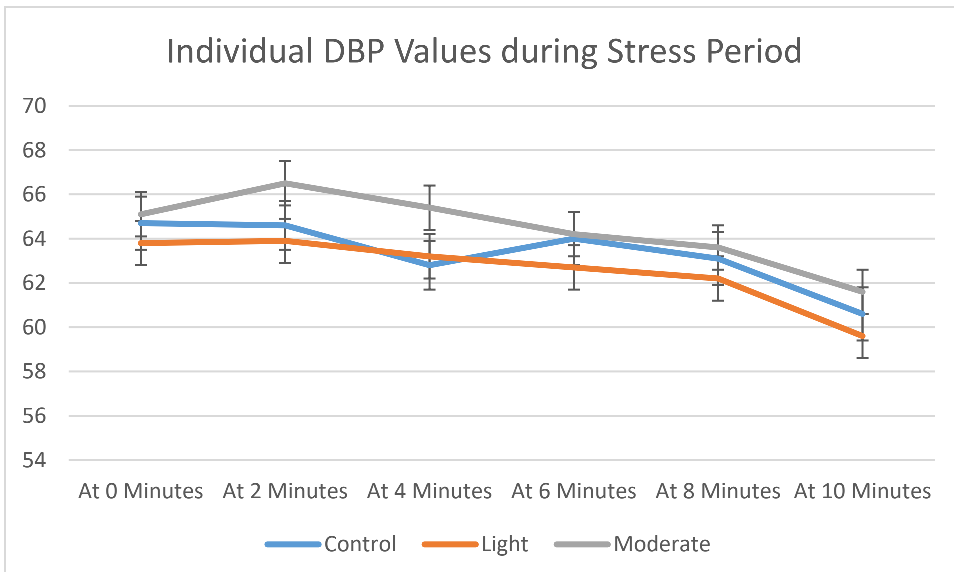


Figure 12. BP Values during Stress Period

In light of these within-task BP differences, we re-analyzed the main analyses with the BP values during the first four minutes of the Stroop rather than the BP values during the entire 10-minute task in a series of ANCOVA models. Similar to the main analyses, we found that group differences in SBP (F (1, 174) = 3.76, p = .025) but not DBP (F (1, 174) = 1.17, p = .31) responses. Again, follow-up analyses showed that the light physical activity group exhibited higher SBP responses than the control (F (1, 115) = 6.66, p = .011) and moderate physical activity (F (1, 115)

= 5.01, p = .027) groups. No significant differences emerged in SBP responses to the first four minutes of the Stroop between the moderate physical activity and control groups (F (1, 116) = 0.08, p = .77). These data suggest that BP responses to the Stroop task were elevated in the first half of the task relative to the last half of the task, but this within-task habituation did not alter the pattern of findings shown in the main analyses.

3.5.2 Engagement with the Stroop Task

In an effort to determine why the physical activity groups did not show reduced BP responses compared to the control group, we explored the possibility that the few group differences in BP responses to the Stroop task noted earlier were a function of group differences in engagement with the Stroop task. Here, we reasoned that the physical activity groups may have been cognitively activated following their physical activity bouts, which, in turn, may have increased their engagement in the Stroop task. Accordingly, increased engagement in the Stroop task may have contributed to elevated BP responses during the Stroop relative to less engaged counterparts. This hypothesis would explain why the light physical activity group showed higher BP responses to the Stroop relative to the seated controls, who may not have experienced this cognitive activation.

Unfortunately, we lacked self-report measures of perceived engagement with the Stroop task to test this hypothesis. Instead, we considered performance during the Stroop task as a proxy measure of engagement. We considered several indices of performance due to the titration algorithm of the Stroop task. Recall that this version of the Stroop task automatically titrated between trials based upon participant performance, such that more consecutively correct responses resulted in shorter allowed response time on subsequent trials, and consecutively incorrect responses resulted in longer allowed response time on subsequent trials. Due to this dynamic nature of the Stroop task, non-responses during certain trials may be due to the extremely brief allowed response time that occurred after a series of consecutively correct answers. For example, 13.5% of all Stroop trials had less than one second of allowed response time. In other words, these non-responses may not be due to an incorrect response but due to the lack of opportunity to make a response. Thus, we evaluated five indices of Stroop performance to account for the titrated nature of Stroop task: averaged allowed response time, average response time by the participant, percentage of trials with no responses, raw accuracy, and adjusted accuracy. Raw accuracy represents the percentage of correct responses across all trials, and adjusted accuracy represents the percentage of correct responses after removing non-responses from the denominator. This adjusted accuracy index reflects the accuracy among trials in which responses were provided.

In light of the within-task BP habituation noted earlier, we considered that these Stroop performance indices may vary across group *and* by epoch. For example, Stroop performance may be higher earlier in the Stroop task when BP was most pronounced relative to the latter half of the test. Accordingly, we compared group differences in the five Stroop performance indices for: a) the entire 10-minute Stroop task; b) in the first four minutes of the Stroop task compared to the last six minutes; and c) at each interval that BP readings were collected during Stroop task (at 0, 2, 4, 6, 8, 10 minutes).

ANOVA models here found no group differences in any of the five performance measures for the entire 10-minute Stroop task, between the first four minutes and last six minutes of the Stroop, or at any of the two-minute intervals. These comprehensive analyses clearly demonstrate that there were no discernable group differences in Stroop performance for any of the experimental groups. We conclude from these findings that Stroop performance, and, by inference, degree of engagement in this laboratory task, did not contribute to the larger BP responses in the light physical activity group.

3.5.3 Affective differences

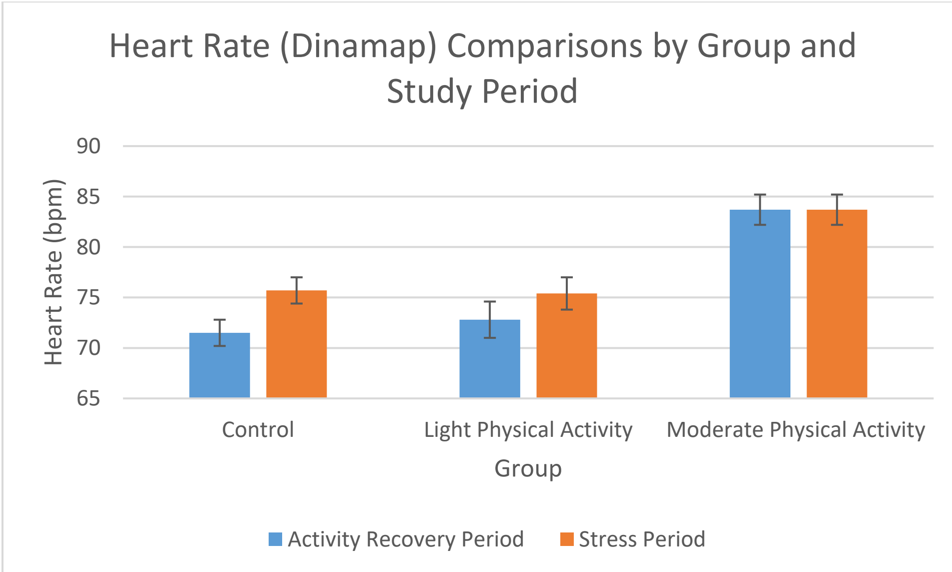
We compared momentary affect derived from the Activation-Deactivation Affect Checklist following the activity recovery period between the three groups as a potential moderator of BP responses. First, we sought to understand if there were group differences in momentary affect for the two bipolar dimensions, Energetic Arousal and Tense Arousal. ANOVA models controlling for race indeed showed significant group differences in Energetic Arousal (F (2, 175) = 4.56, p = .01) and Tense Arousal (F (2, 175) = 3.65, p = .028). Post hoc Tukey tests reveal significantly higher Energy Arousal for the moderate physical activity group compared to controls, and significantly lower Tense Arousal for the light physical activity groups compared to controls (p's < .05). These findings suggest that moderate physical activity participants experienced more energy and vigor compared to controls following the activity recovery period, whereas light physical activity participants experienced more calmness than controls. Despite these group differences, ANCOVA models covarying for baseline BP values and race found no significant main effect or group interaction of Energetic Arousal or Tense Arousal on SBP or DBP responses to stress. These data suggest that group differences in affective states following physical activity did not influence BP responses to the Stroop task.

3.5.4 Potential Moderators

We examined potential moderators of BP responses in series of separate ANCOVAs. Consistent with the above analyses, all models controlled for initial baseline values and race. There was a main effect of sex on SBP (F (1, 171) = 7.33, p = .0075) and DBP (F (1, 171) = 6.14, p = .014) responses, such that BP responses were higher in males than in females. There were no significant interactions with group on SBP (F (2, 171) = 0.40, p = .67) or DBP (F (2, 171) = 1.61, p = .20) responses. There was no main effect of race (White vs. non-White) on SBP (F (1, 172) = 2.29, p = .13) or DBP (F (1, 172) = 0.00, p = .98) responses, nor were there significant interactions with group on SBP (F (2, 172) = 1.65, p = .19) or DBP (F (2, 172) = 1.01, p = .38) responses. There was no main effect of habitual physical activity on SBP (F (1, 170) = 2.19, p = .14) or DBP (F (1, 170) = 0.13, p = .72) responses, nor were there significant interactions with group on SBP (F (2, 170) = 0.55, p = .57) or DBP (F (2, 170) = 1.49, p = .24) responses. There was no main effect of BMI on SBP (F (1, 171) = 0.66, p = .41) or DBP (F (1, 171) = 0.08, p = .78) responses. A marginally significant interaction of BMI by group emerged for SBP (F (2, 171) = 2.62, p = .076) but not for DBP (F (2, 171) = 0.30, p = .74) responses.

3.5.5 MAP and HR reactivity

In order to understand how physical activity may influence other cardiovascular responses to stress, we conducted a series pf ANCOVA analyses with MAP responses to the Stroop as well as HR collected from our two instruments: HR Polar and HR Dinamap. Like the SBP and DBP responses, these values were calculated as the arithmetic difference in averaged values during the final two readings of the activity recovery period and the entire Stroop task. Omnibus ANCOVA analyses showed significant group differences in both HR Polar (F (2, 173) = 4.50, p = .0125) and HR Dinamap (F (2, 141) = 13.83, p < .0001) responses (see Figure 13) but marginally significant group differences in MAP responses (F (2, 174) = 2.55, p = .08). Follow-up ANCOVA models found significantly smaller responses among individuals in the moderate activity group compared to individuals in both the control (HR Polar: F (1, 115) = 5.79, p = .018; HR Dinamap: F (1, 93) = 13.34, p = .0004) and light physical activity groups (MAP: F (1, 115) = 6.15, p = .015; HR Polar: F (1, 115) = 7.49, p = .007; HR Dinamap responses: F (1, 94) = 25.98, p < .0001). There were no significant differences in the magnitude of responses between the light physical activity and control groups for MAP (F (1, 115) = 2.28, p = .13), HR Polar (F (1, 145) = 0.38, p = .54), or HR Dinamap (F (1, 93) = 1.76, p = .19).



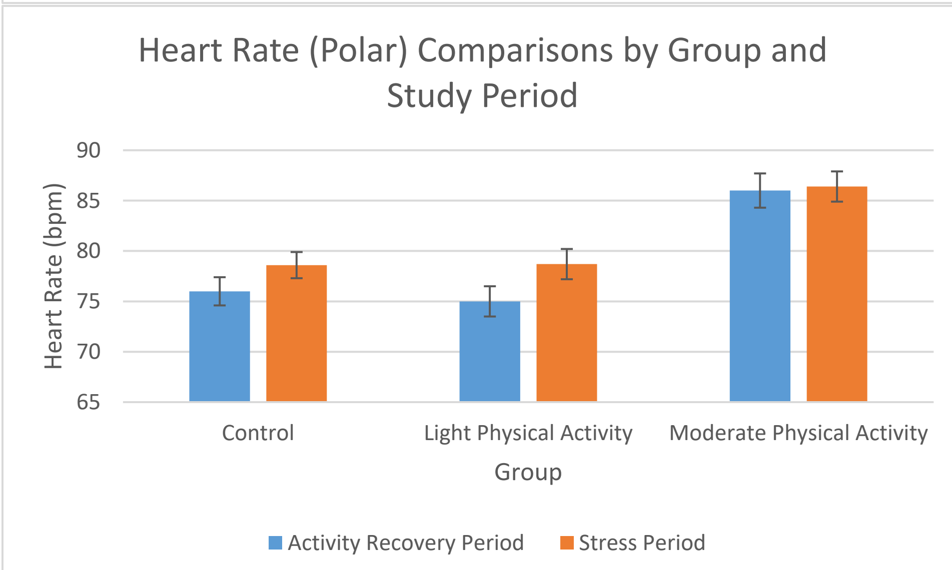


Figure 13. Heart Rate Comparisons by Group and Study Period

Following the same analytic plan outlined in the main analyses, we removed those who failed to return to initial baseline values during the activity recovery period. After removing these non-recoverers, omnibus ANCOVA analyses no longer showed significant group differences in the magnitude of responses for MAP (F (2, 155) = 1.77, p = .17), HR Polar (F (2, 149) = 1.35, p = .70), or HR Dinamap (F (2, 120) = 2.92, p = .057). Though this omnibus ANCOVA model only found marginally significant group differences for HR Dinamap, we conducted follow-up analyses for each of the three group-level comparisons (light physical activity vs control, moderate physical activity vs control, light vs moderate physical activity) in the event that significant group differences emerged for only two of the three groups. Unlike the model including non-recoverers, follow-up ANCOVA models excluding non-recoverers showed that the HR Dinamap responses in the moderate physical activity group were no different from controls (F (2, 72) = 1.62, p = .20). However, participants in the moderate physical activity group continued to show smaller HR Dinamap responses than participants in the light physical activity group F (2, 72) = 6.10, p = .01). See Figure 14 for an illustration of these effects. Consistent with the main analyses, these exploratory findings continue to support the notion that neither physical activity group showed attenuated physiological responses to stress compared to the control group. However, these exploratory analyses did suggest that the moderate physical activity group showed lower HR responses to the Stroop task only when compared to the light physical activity group.

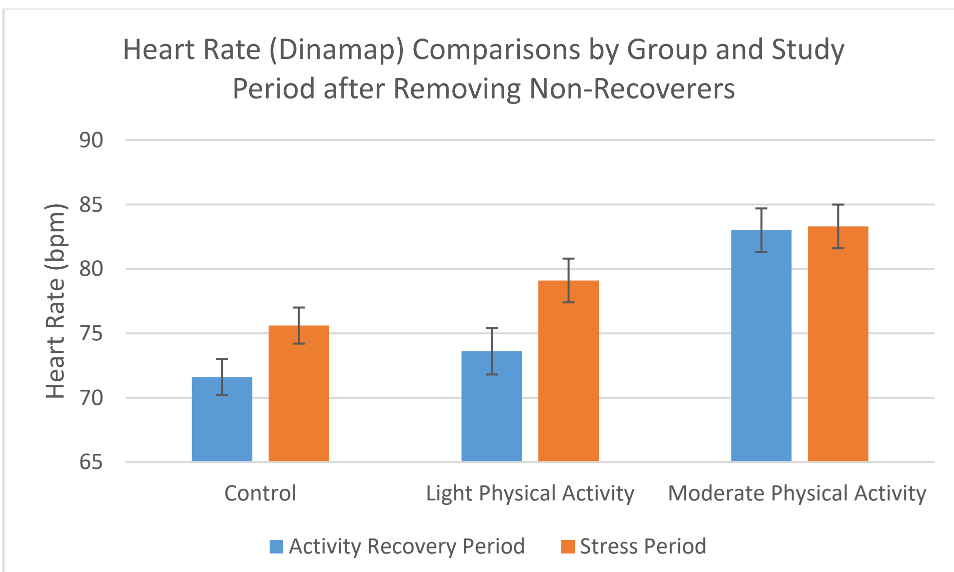


Figure 14. Heart Rate Comparisons by Group and Study Period after Removing Non-Recoverers

3.5.6 BP Recovery

Next, we considered how physical activity may enhance BP recovery to stress. We operationalized recovery in one of two ways: arithmetic difference between average BP values during the stress recovery period and the activity recovery period (“change score”), area-under-the-curve with respect to ground ("AUGg") which reflects the degree and speed of recovery. Two recovery measures were adopted because there is a lack of consensus in the literature about how best to quantify BP recovery (see Linden et al., 1997). Adopting the formula outlined by Pruessner et al. (2003), the AUC_g recovery parameter included the final BP reading during the Stroop period to reflect the start of the recovery period. SBP and DBP values at the initial baseline period were included as covariates for each respective model. For the AUC_g analyses, 14 participants were removed from analysis due to missing datapoints. Table 6 depicts the means and standard deviations of these metrics for each of these groups.

Table 6. Mean (SD) of BP Recovery Values by Recovery Parameter

Table 6.

Mean (SD) of BP Recovery Values by Recovery Parameter

		Entire Sample (N = 179)	*Control Group (n = 60)*	*Light PA Group (n = 59)*	*Moderate PA Group (n = 50)*
Recovery Parameter		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Change Score					
	SBP	-0.41 (4.9)	0.20 (5.2)	0.32 (4.3)	-1.78 (4.8)
	DBP	0.77 (4.1)	1.6 (4.8)	0.81 (3.5)	-0.10 (3.6)
AUCg					
	SBP	548.6 (41.0)	545.9 (43.0)	546.8 (40.2)	553.0 (40.1)
	DBP	306.7 (37.9)	309.7 (43.5)	299.9 (35.1)	310.3 (34.4)

Note. SBP = Systolic Blood Pressure. DBP = Diastolic Blood Pressure. AUCg = Area-under-the-curve with respect to ground. The change score was calculated as the arithmetic difference between average BP values during the stress recovery period and the activity recovery period. AUCg was calculated according to the formula outlined by Pruessner et al. (2003). The AUCg recovery parameter included the final BP reading during the Stroop period to reflect the start of the recovery period. SBP and DBP values at the initial baseline period were included as covariates for each respective model.

Omnibus ANCOVAs using the change score recovery value showed significant group differences for SBP recovery (F (2, 174) = 4.66, p = .01) and a marginally significant difference for DBP recovery (F (2, 174) = 2.91, p = .057). Follow-up analyses showed that there was steeper SBP and DBP recovery for the moderate physical activity group compared to the control (SBP: F (1, 116) = 5.87, p = .017; DBP: F (1, 116) = 5.79, p = .018) and light physical activity groups (SBP: F (1, 115) = 9.60, p = .002) except for DBP (F (1, 115) = 3.59, p = .06). No significant differences emerged between the light physical activity group and controls (SBP: F (1, 115) = 0.09, p = .77; DBP: F (1, 115) = 0.88, p = .35). After removing non-recoverers, the moderate physical activity group continued to show significantly steeper SBP and DBP recovery compared to control (SBP: F (1, 108) = 6.21, p = .01; DBP: F (1, 108) = 5.46, p = .02) and light physical activity groups (SBP: F (1, 105) = 8.91, p = .004). The change score recovery findings suggest enhanced BP recovery for the moderate physical activity group relative to light physical activity and control groups. See Figure 15 for plotted SBP and DBP values across the activity recovery period and stress recovery period.

However, omnibus ANCOVAs using the AUC_g value showed no group differences for SBP (F (2, 160) = 0.16, p = .85) or DBP recovery (F (2, 160) = 0.55, p = .57). Plotted individual data points in Figure 16 do not reflect apparently group differences, especially for SBP recovery. These null group differences persisted after removing non-recoverers from the activity period. Contrary to the change score recovery parameter, the AUC_g would suggest no differences in recovery across the experimental groups.

In light of the observed BP habituation to the Stroop task noted earlier, we questioned whether the BP values at the end of the stressor period were different from the BP values during the stress recovery period. Paired t-tests of the last two BP readings of the Stroop compared to the averaged recovery period BP values did not show significant BP differences among control (SBP: *t* (59) = -1.08, *p* = .28; DBP: *t* (57) = -1.73, *p* = .09), light physical activity, (SBP: *t* (57) = 1.87, *p* = .07; DBP: *t* (57) = -22, *p* = .82), or moderate physical activity (DBP: *t* (58) = .03, *p* = .97) groups. Only significant differences in SBP values emerged for the moderate physical activity group (*t* (59) = 3.33, *p* = .0015), such that BP values during the recovery period were significantly lower than the last two readings observed during the Stroop task. These results suggest that BP recovery to stress was not significantly different from those BP responses to stress exhibited toward the end of the stressor for the light physical activity and control groups; only the SBP recovery to stress was significantly lower than SBP responses to stress in moderate physical activity participants.

4.0 Discussion

The current investigation sought to understand the effects of brief bouts of light physical activity on blood pressure responses to psychological stress. In a between-person, single-session experiment, we randomized 179 healthy, young adults to 15 minutes of light physical activity, 15 minutes of moderate physical activity, or 15 minutes of sitting before engaging in a 10-minute computerized Stroop Color-Word Interference Task. We hypothesized that participants in the light physical activity group (Hypothesis 1) and moderate physical activity group (Hypothesis 2) would exhibit lower BP responses to stress (BPRS) than the seated control group We also tested for group differences in BPRS between the two physical activity groups (Exploratory Hypothesis).

4.1 Light Physical Activity Findings (Hypothesis 1)

Contrary to our stated hypothesis, we surprisingly found that the light physical activity group showed *higher* SBP responses to the Stroop task relatively to the control group. In an effort to consider several alternative explanations of these findings, this effect persisted after removing participants who did not return to their initial baseline values following physical activity and after restricting analyses to the more pronounced SBP responses observed earlier in the Stroop task period. The non-significant group differences in DBP responses also failed to support our hypothesis. Not only did this study fail to support our primary hypothesis, we found a fairly robust finding in the opposite direction.

Notwithstanding, these unexpected findings make an important contribution to a small, inconclusive literature on the effects of brief bouts of light physical activity on BP responses to stress. As noted earlier, studies purportedly examining lighter-intensity bouts of physical activity and BP responses to stress employed moderate-intensity activity (Alderman et al., 2007), failed to elicit an increase in BP during the stressor task (Ledochowski et al., 2015), or involved ambiguous intensity of the physical activity (Taylor & Katomeri, 2006; Taylor & Oliver, 2009), or. In evaluating how our findings differed from the previous studies that appeared to find lighter-intensity physical activity as a moderator of the effects of laboratory-based stress responses, we thought that it might be useful to revisit these studies we initially thought might be most comparable to our own. Taylor & Katomeri (2006) concluded that lighter physical activity was associated with lower BP responses to the Stroop task compared to the controls in a sample of 60 healthy smokers who were randomized to either 15-minutes of brisk semi-self-paced walking or control condition. Likewise, Taylor and Oliver (2009) concluded that lighter physical activity was associated with lower BP responses to the Stroop task in a sample of 25 regular chocolate eaters adopting a within-person design. However, BP readings associated with BP responses to stress in each of these studies occurred immediately after the conclusion of the stressor task; instead of measuring BP responses to the stressor tasks, these two studies measured BP *recovery* to stress.

Unlike this prior work, objective and self-reported indices of physical activity in our current investigation suggest that our participants indeed engaged in light bouts of physical activity, and our Stroop task did successfully increase levels of both blood pressure parameters. In this regard, we are the first study to our knowledge to test the effects of light physical activity on blood pressure responses measured during laboratory-based stressor tasks. More importantly, our findings from a large, well-designed study strongly indicate that light physical activity does not attenuate blood pressure responses to laboratory-based stressors in healthy, young adults.

It should be noted that the BPRS in the light physical activity group, though significantly higher than in the control group, were not markedly elevated. The group-level BP responses of 3.92 mmHg SBP observed during the entire stress period in the light physical activity group (5.26 mmHg in the first four minutes of the stress period) is comparable to other recent studies employing a computerized Stroop task. For instance, Gianaros et al. (2017), a brain imaging study without an exercise component in its design, found mean SBP responses to the Stroop were 4.95 mmHg (95% CI = 4.23–5.69) in a healthy sample of adults. Our light physical activity participants exhibited SBP responses comparable to Stroop tasks in non-exercise studies, and in this respect, the absolute BPRS values in our light physical activity group are not notably elevated. BPRS values in the light physical activity group are relatively higher only in the context of the control group, which as we discuss below, exhibited unusually low BPRS. In comparing the BPRS of our light physical activity group to a non-excise study with a comparable stressor task, our study does not suggest that engagement in light physical activity harmfully exacerbates BPRS.

4.2 Moderate Physical Activity (Hypothesis 2)

Unlike with our light physical activity findings, participants in the moderate physical activity group did not show significantly different SBP and DBP responses than participants in the control group. These null effects persisted after removing non-recoverers from analyses or restricting analyses to the more pronounced SBP responses observed earlier in the Stroop task period. These null findings are somewhat at odds with conclusions drawn in the established literature. Hamer and colleagues (2006) concluded in their meta-analysis of 15 studies that brief bouts of moderate-to-vigorous physical activity were indeed associated with reduced laboratory-based BPRS. However, this literature, especially the studies included in the meta-analysis, has considerable variability in study design, such as sample size, within-or between subject comparisons, stressor task(s), and the intensity, duration, and type of physical activity used, as well as participant characteristics, such as sex, age, hypertensive status, and habitual physical activity or fitness levels. Due to this heterogeneity, our results involving the effects of moderate physical activity on BPRS may be best understood when compared to studies most similar to ours in terms of design features and participant characteristics.

In this respect, our findings involving moderate physical activity and BPRS are not too unusual. In a sample of 80 “low to moderately fit”, college women, Hobson and Rejeski (1993) found no DBP response differences to a Stroop task following 10-minutes of vigorous cycling compared to 10-minutes of sitting on the exercise bicycle with no movement. The authors did find significant SBP reductions at 10 minutes as well as significant SBP and DBP responses for 25- and 40-minutes of physical activity. Though this study used vigorous-intensity physical activity for its manipulation, this study was similar to ours in their use of a brief (10 minute) bout of physical activity, their use of a Stroop task, and their sample of less-fit college women. Roth (1989) found no condition effects for SBP or DBP responses to a mental arithmetic task between the exercise (20 minutes of moderate-intensity cycling) and waiting-period control groups among 80 active and inactive college students. Though this study also included active college students and a mental arithmetic task as the stressor, this study was similar to ours in terms of the brief, moderate physical activity bout and a sample involving inactive college students. Similar to the Roth study, Steptoe et al. (1993) randomized 36 active and 36 inactive men to 20 minutes of light activity, moderate activity, or vigorous activity. Though statistical comparisons between the light and moderate activity conditions were not reported, the graphs indicate that there were minimal to negligible differences between the light and moderate activity conditions for SBP and DBP responses to mental arithmetic and public speech tasks. Reduced responsivity was only observed in the vigorous physical activity condition. Like our study, this study did not find considerable differences in BP responses following light and moderate physical activity bouts. Contrary to the overall conclusions drawn in Hamer et al. (2006), these three between-person designs did not show consistent BP reductions following brief bouts of moderate physical activity.

Instead, these studies as well as the meta-analysis by Hamer and colleagues may indicate attenuated BP responses following brief bouts of *vigorous* physical activity rather than moderate physical activity. The Hamer meta-analysis noted that seven of the eight studies that employed vigorous-intensity physical activity (defined there as greater than or equal to 60% VO_{2max} or 75% HRR) demonstrated significant reductions in BPRS following physical activity periods (Bartholomew, 2000; Boone et al., 1993; Brownley et al., 2003; Probst et al., 1997; Rejeski et al., 1991; Roy & Steptoe, 1991; Steptoe et al., 1993), whereas only 4 of 10 studies involving light or moderate physical activity (less than 60% VO_{2max} or 75% HRR) demonstrated significant reductions of BPRS following these physical activity periods (Hobson & Rejeski, 1993; Rejeski et al., 1991; Rejeski et al., 1992; West et al., 1998). Though design and participant characteristics may also contribute to these differences (e.g., some of the moderate-intensity activity studies had < 10 participants or used non-standard stressors), previous literature suggests that reductions in BPRS are more consistently shown following vigorous physical activity than for moderate physical activity. In light of our current findings, moderate physical activity may not be intense enough to significantly reduce BPRS.

4.3 BP Recovery

In an exploratory fashion, we probed for potential group differences in BP recovery using two parameters: change score and area-under-the-curve (AUC_g) with respect to ground. As mentioned previously, two recovery measures were adopted because there is a lack of consensus in the literature about how best to quantify BP recovery (see Linden et al., 1997). Here, we found that change score BP recovery was steeper in the moderate group than among controls, even after removing non-recoverers. However, there were no differences in AUC recovery between the three experimental groups. In fact, BP values in the final few minutes of the stress period were generally not significantly different from the BP values during the recovery period. Thus, if BP responses to the stressor were not significantly different from BP values during the recovery period, and no group differences were observed during the recovery period, it is difficult to conclude that there were group differences in the extent of BP recovery to stress. Due to the inconsistency between these two BP recovery parameters, we are cautious to conclude that the change score recovery parameter finding reflects enhanced recovery among moderate physical activity participants.

It is possible that these significant change score recovery findings observed for the moderate physical activity group were driven by somewhat higher BP levels – albeit non-significantly different from the other groups – at the end of the activity recovery period, a trend that persisted even after removing individuals whose BP did not return to initial baseline values. Figure 15 further demonstrates that there does not appear to be considerable differences in SBP or DBP values during the stress recovery period relative to controls. To some extent, the change score recovery parameter here could simply reflect continued recovery from the physical activity bout rather than from the stressor itself. These findings underscore the difficulty in interpreting BP recovery to stress, and our interpretations are further challenged by the additional of a physical activity manipulation. Future research may consider adding a separate control group that receives the moderate physical activity bout but no stressor task to aid in teasing apart post-physical activity recovery from post-stress recovery. Despite being inconclusive, our findings here raise important questions about best methodological practices to measures BP recovery to stress in physical activity studies.

4.4 Control Group Findings

Perhaps the most surprising finding from the current investigation was the markedly low SBP responses in the control group. The low SBP responses in the control group are especially unexpected provided that the experimental procedures were nearly identical across all three groups. It is highly unlikely that the researcher unduly introduced bias only in the control group during the early study period – when most verbal and physical interactions with the participant occurred – as both the researcher and participant were blinded to group assignment until after the end of the initial baseline period. In reviewing the few procedural differences between the three groups, greater scrutiny is given to the unique task completed by controls: the 15-minute computerized vanilla baseline task. The following section considers differences in task and environmental novelty, as well as the potential influence from the COVID-19 pandemic, may have impacted SBP responses in control participants. Here, we weigh findings from prior work that support and counter these interpretations.

One interpretation for these unexpected results is that the control participants may have had experienced less novelty when exposed to the Stroop task compared to the two physical activity groups due to their prior engagement with the vanilla baseline task. Here, controls engaged in a 15-minute computerized, non-demanding task that involved counting the number of times a colored square appeared on the screen. In effect, the Stroop task was the second computerized task that they experienced during the session – albeit the only computerized task designed to be stressful. Consequentially, these participants may have experienced less task novelty to the computerized Stroop task due to this prior exposure and that may have contributed to their less pronounced BP response to the Stroop task.

Reductions in task novelty have been previously shown to be associated with alterations in cardiovascular responses to stress. Kelsey et al. (1999) showed in a sample of healthy undergraduate men that participants who underwent a minimally demanding mental arithmetic task (subtracting by 3) exhibited smaller pre-ejection period (PEP) responsivity to a subsequent, more demanding mental arithmetic task (subtracting by 7) than naïve participants who only underwent a seated baseline period prior to this demanding mental arithmetic task. These findings suggest that reductions in cardiac responsivity to demanding tasks can be observed after prior exposure to a less-demanding task in a single-session experiment. In light of these findings, the prior exposure to the minimally-demanding vanilla baseline task in our own single-session experiment may have inadvertently primed control participants to have low responses to our stress task.

Relatedly, another interpretation for these lower BPRS in the control group is that the control participants may have experienced less environmental novelty during the experimental compared to the two physical activity groups. Rather than leave the reactivity chair after the initial baseline period to engage in physical activity on the treadmill, control participants continued to be seated for the 15-minute computerized vanilla task and the subsequent activity recovery period before the stressor task, which was also administered from the reactivity chair. In this process, control participants had more uninterrupted exposure to this particular testing environment that prefaced the Stroop task than the physical activity groups. Consequentially, these control participants may have acclimated to the testing environment where the Stroop task was administered, and, as argued with respect to the reduced task novelty, this characteristic of the laboratory experience may have contributed to their less pronounced BP responses to the Stroop task.

We are somewhat skeptical that potential differences in task and environmental novelty contributed to the attenuated BPRS in the control group for three reasons: the extensive use of the vanilla baseline task in the literature, lengthy baseline periods not impacting BP responsivity, and comparability of our inactive control protocol to other studies. First, the vanilla baseline task has been used extensively in prior work without evidence or concern for unduly influencing BP responses to subsequent stressors (e.g., Kamarck et al., 2003). Significant reductions in BP responses following the vanilla baseline task likely would have been observed in prior work. Second, lengthy baseline periods prior to the start of stressor task(s) have not yielded low BP responses to subsequent stressors in previous studies. For instance, Miller and Ditto (1991) showed pronounced SBP and DBP responses to a shock-avoidance task following a one-hour resting baseline period in a sample of 48 healthy, young men, and Jennings et al. (1992) found comparable cardiovascular responses to tasks which followed either two 10-minute or 20-minute vanilla baseline conditions. In the current study, control participants sat for 45 minutes prior to the stressor period (see Figure 4 for the procedure timeline). The extant literature does not suggest that this 45-minute period alone should have impacted subsequent SBP responses. Finally, our protocol is not unusual among other physical activity-BP reactivity experiments. Several studies in this literature have used inactive control periods of equivalent duration to the physical activity periods and still found pronounced BP responses among control participants. Hobson and Rejeski (1993) even had the control participants sit on the cycling ergometer for 10 minutes without movement and observed pronounced SBP responses (12.55 mmHg) to a 3-minute Stroop task.

Though our control group may have experienced reductions in task and environmental novelty, the extant literature does not clearly indicate that the current study's experimental design would have unduly influenced the magnitude of response in the control group. However, no other study comparing the effects of acute bouts of physical activity on BP responses to stress had asked controls to engage in a vanilla baseline task during a lengthy sitting period prior to a stressor. In light of the unique protocol for the control group in the current investigation, it cannot be ruled out that the combination of reduced environmental and task novelty factors may have contributed to the low SBP responses in our control group.

A final consideration for the unexpected findings on the magnitude of response to the Stroop task is that in-person data collection during the COVID-19 pandemic may have influenced our results. In a time when in-person research was closely regulated to mitigate risk for COVID-19 transmission, our efforts to create a safe, clean environment through strict adherence to mask wearing, social distancing, and cleaning may have fostered a sense of security during the experimental session that would otherwise not have been fostered prior to the COVID-19 pandemic. The sample likely consisted of participants who were comfortable in such an environment; potential participants who would have been anxious or uncomfortable in this testing environment presumably would not seek out or agree to volunteer for in-person research. This effect may have been most apparent in control participants as they had remained masked for the entirety of the visit. Outside of the experimental design, it is possible that participants were more habituated to computer-based stressors during the study recruitment period. At the University of

Pittsburgh, in-person instruction primarily shifted to remote, computer-based instruction. Traditional real-life stressors for this population, like exams, likewise shifted to be computer-based. It is possible that computerized cognitive stressors may not have been perceived nearly as stressful in this population due to their increased experience with other computerized stressors. Interpretation of these findings may be obfuscated by the unprecedented testing environment due to the COVID-19 pandemic.

4.5 Reevaluating Thomas et al. (2019)

The impetus for this current investigation was to better understand exploratory findings from Thomas et al. (2019), which found a relationship between light physical activity and blood pressure responses to psychosocial stressors in daily life in a midlife sample of healthy adults. Despite enhanced experimental control over the physical activity intensity, duration, and nature of the stressor, the current study found no relationship between brief bouts of light physical activity and attenuated BP responses to stress. There are several possible explanations for the discrepancy between these two studies. First, sample characteristics differences could account for these different findings. Though both studies involved healthy adults free of cardiovascular disease and antihypertensive medications, the current investigation recruited young adults (18-24 years old) who did not meet national guidelines for the minimum recommended levels of physical activity, whereas Thomas et al (2019) recruited midlife adults (30-54) irrespective of physical activity habits. The interaction between age and physical activity habits may have contributed to these discordant findings. Rates of light physical activity have been shown to decrease with age (Hawkins et al., 2009), and BP responses to stress have been shown to increase with age (Uchino et al., 2010). Consequentially, less frequent light physical activity and generally higher BP responses to stress may improve the ability to detect lower BP responses following periods of light physical activity. It is unlikely that differences in habitual physical activity directly accounted for these different findings as recent physical activity had an independent effect on BPRS in the Thomas et al. (2019) study after adjustment for habitual physical activity, and the current investigation did not find self-reported physical activity to moderate BPRS.

Another potential reason for the discrepant findings across these two studies involves differences in the precision with which the timing of the physical activity bout and stressor were measured. Accelerometry-derived measures of physical activity used in the Thomas et al. (2019) ambulatory study do not provide detailed information on the type of activities being performed. Furthermore, participants were asked to rate stressors in the 10 minutes prior to the ambulatory blood pressure reading. It is unknown whether the physical activity bout concluded before the stressor, occurred simultaneously with the stressor, or even began after the stressor. The tentative recovery findings observed in the current study suggest that the purposed attenuated BP responses shown in the ambulatory study could very well have been attenuated *recovery* to stress. The current experimental study raises questions on the potential role of BP recovery in understanding the ambulatory study.

4.6 Limitations and Future Directions

This study is not without limitations. First, screened individuals who met national guidelines for the minimum recommended amount of physical activity were excluded from study participation. Considering that nearly 47% of screened individuals were excluded for this reason, these results may not extend to physically active young adults. BP responses following light physical activity may be more or less pronounced among highly active adults.

A second limitation of this work is the use of a prolonged, single cognitive stressor task. The 10-minute computerized Stroop task used here did evoke statistically significant elevations in BP responses, however, this BP response was not sustained throughout the 10-minute period. Exploratory analyses showed that the BP readings from the first four minutes of the Stroop task as the outcome variable yielded a similar pattern when compared to analyses using all BP readings during the stress period. These analyses suggest that the longer Stroop task employed here did not mask group differences, but future research should consider that a shorter Stroop task would have been sufficient to detect physical activity-related group differences.

Across the entire sample, the BP responses to the Stroop task were relatively low. These relatively low BP responses may have limited our ability to detect group differences in BP responses, such as those between moderate physical activity and controls. It is possible that tasks associated with a high magnitude of BP responses may have aided the detection of group differences. The sound inference component was added to the Stroop task to enhance the stressfulness of the task, but the magnitude of responses observed in this study did not appear to be markedly higher than those responses found in studies using the Stroop task without sound interference (e.g., Gianaros et al., 2017).

In addition to or in place of sound interference, the use of monetary incentives may increase the magnitude of BP responses. Prior work has shown a twofold increase in BP responses to a computerized Stroop task with a performance-related monetary incentive relative to a non-incentivized condition (Waldstein et al., 1997). Alternatively, complementing or replacing the Stroop task with a speech or other social stressor task may achieve larger BP responses than cognitive tasks (e.g., Al'Absi et al., 1997; Kamarck & Lovallo, 2003). However, tasks with speaking components are known to confound BP readings (Lynch et al., 1981) and have lower test-retest reliability than cognitive tasks (Kamarck & Lovallo, 2003). Future work should consider a battery of brief cognitive and stressor tasks, or at minimum, employ a shorter Stroop task with a monetary incentive, to evoke a large BP response to aide in detecting group differences.

Additional physiological data across the study periods may shed insight into why light physical activity participants exhibited higher BPRS than the control group. There are numerous central and local adaptations of the cardiovascular system during a physical activity bout and the following recovery period. Though some physiological responses following physical activity should not necessarily prime the body to evoke enhanced BP responses to subsequent psychosocial stressors, such as sustained post-activity vasodilation within the vascular beds of previously active skeletal muscles, it is possible that some physiological parameters remained elevated following light physical activity that contributed to this group's larger BPRS. For instance, cardiac output (CO), the amount of blood ejected from the heart into circulation that is critical for modulating blood pressure levels, increases proportionally to the intensity of physical activity (Guyton & Hall, 2000; Rowell, 1986) and remains elevated up to 30 minutes into the physical activity recovery period (Halliwill et al., 2013; Piepoli et al., 1993). However, it remains unclear why both physical activity groups did not show BP changes consistent with this effect. These puzzling findings may underscore the value of including more parameters of cardiovascular responses to physical and stress above and beyond blood pressure. Future work should measure underlying physiological mechanisms during physical activity and stress periods in an effort to understand the enhanced SBP responses to stress in the light physical activity group.

The findings of the current investigation call into question the impact of brief bouts of physical activity on BP responses. In the largest study to date, we failed to find attenuated BP responses to stress after engaging in brief bouts of light and moderate bouts of physical activity; in fact, we found higher BP responses after engaging in light physical activity relative to controls. These convincing findings imply that acute physical activity of light and moderate intensities, in a single-session experiment, does not attenuate BP responses to stress in a sample of healthy, not highly active young adults.

Rather than in acute settings, light and moderate physical activity may moderate BP responses to stress only after long-term adaptations to physical activity. This idea would be consistent with findings from a systematic review and meta-analysis that we have recently completed on the effectiveness of physical exercise interventions in the improvement of blood pressure responses to psychosocial stressors (Thomas et al., in preparation). This work found small but significant reductions in SBP ($g = 0.37$, $p < .0001$) and DBP ($g = 0.25$, $p = .0001$) responses from pre-intervention to post-intervention among 20 aerobic exercise intervention studies of adults ages 18 and older. The average intervention duration was 17 weeks (range: 5 – 72) and 51 total sessions (range: 10 – 192). Though the interventions were predominantly in the moderate-to-vigorous intensity range, a single study in this meta-analysis included a light physical activity group. Boone et al. (1993) randomized 18 borderline hypertensive participants to a 12-week intervention involving three groups: control (no exercise), light activity (40-50% VO_{2max}), or moderate physical activity (70-80% VO_{2max}). The training program consisted of 45 minutes of treadmill walking three times per week at prescribed heart rate ranges. The light physical activity group showed pronounced reductions in SBP ($g = 1.1$, $p = .008$) and DBP responses ($g = 1.5$, $p = .002$) to the Stroop task at post-intervention relative to BP responses at pre-intervention. The decreases in SBP responses to the Stroop were significantly larger in the light physical activity group than in either the moderate physical activity or control groups. Taken together, the findings form the current investigation and Boone et al (1993) suggest that long-term but not short-term engagement in light physical activity may reduce BP responses to stress.

4.7 Conclusions

The current investigation failed to show significantly attenuated BP responses to stress following engagement in light or moderate physical activity relative to seated controls in a laboratory-based experiment of healthy, young participants. Surprisingly, participants assigned to engage in light physical activity showed higher SBP responses to the Stroop task than the control participants. By using a highly controlled laboratory design with clear and consistent measures of both light and moderate physical activity, these findings provide an important contribution to a literature that has been predominately based upon moderate-to-vigorous bouts of physical activity with considerable variability in study design and participant characteristics, and has not clearly examined the relationship between light physical activity and BPRS. Our null and unexpected findings question the effect that brief bouts of light and moderate physical activity may have on BPRS. Mixed findings about enhanced blood pressure recovery to stress following physical activity raise questions about best methodological practices in studies involving physical activity conditions. Future work on light physical activity and reduced BPRS may be more productive through long-term interventions rather than in acute settings.

Appendix A Phone Screening Script

Hello, may I please speak with _________________. My name is _______________, I am calling from the Bout of Light Activity and Stress, or BLAST, Study. I am following up to your interest on the [SONA portal/Pitt+Me registry] to provide more information about our research study. Do you have a few minutes to talk about the purpose of this study and to go through the screening questions to determine your eligibility?

If no: is there a better time that I could call you back?

If yes: Great. The purpose of the BLAST study is to look at the relationship between physical activity and blood pressure changes when stressed. Specifically, we want to determine whether brief bouts of physical activity influences blood pressure responses to stress differently than during periods of sitting.

We will be asking participants to sit or walk at a light or brisk pace for 15 minutes. We will collect blood pressure readings before and after this 15-minute period. We will also ask participants to complete a computerized stress task. Blood pressure readings will be collected during and after this stress task period. Participants will then complete a series of questionnaires about their physical activity habits, mood, and stress levels. It will require one study visit which will last approximately one hour and 35 minutes.

Do you have any questions or concerns? Now that you have a basic understanding of the study, do you think you might be interested in participating?

If no: Thank you very much for your time. [end call].

If yes: Before enrolling people in this study, we need to determine if you may be eligible to participate. I would now like to ask you a series of questions about your health and physical activity habits. It will take approximately 10 minutes of your time. If any questions make you uncomfortable, you can refuse to answer. All of your information will be kept strictly confidential; your name will never appear on any research materials. Remember, your participation is voluntary and you can quit at any time. Do I have permission to ask you the questions to determine your eligibility?

VERBAL CONSENT OBTAINED: Yes ❑ No ❑

By: ______________________________ Date: _________________

If no: Thank you very much for your time.

May I please ask why you do not wish to participate (choose all that apply)?

1.Don't know
2.Refused
3.Not interested
4.Time concerns (too much time/too many appointments)
5.Inconvenient (scheduling, location)
6.Not enough money
7.Transportation/Lives too far away
8.Health reasons
9.Personal reasons
10. Other (specify) ____

____

Thank you. Any information collected about you during this phone call will remain confidential. Have a nice day/night. Good-bye.

If yes: [Proceed to telephone screening form].

<u>Part 1. Demographic and Health Information</u>
Please provide the following information to the best of your ability.
1. Age2. Date of Birth3. Gender
_________ / ____ / ________ Female
(month / day / year)____ Male
____ Other (please specify)

4. Do you currently take any medication prescribed by a doctor for hypertension or high blood pressure?
___Yes

-Please specify: ____
___No

5. Have you ever had a heart attack, congestive heart failure, angina, or atrial fibrillation?
___Yes
-Please specify: ____
___No

6. Have you ever had bypass surgery, a stent, open heart surgery, balloon angioplasty, or a pacemaker?
___Yes
-Please specify: ____
___No

7. Have you ever been diagnosed with heart valve problems or a heart murmur for which you are followed by a heart doctor?
___Yes
-Please specify: ____
___No

8. (For women) Are you currently pregnant?
___Yes
___No

9. Do you have any injury or physical disability that limits your ability to walk on a treadmill?
___Yes
-Please specify: ____
___No

Part 2. Physical Activity Screening Questions

Thank you. [For Pitt+Me participants, they will be asked permission to be further contacted by the BLAST study PI to do the physical activity screening questions. For SONA participants, the screener will continue with this script.]

I am now going to ask you about your physical activity habits. First, I am going to ask about vigorous activities, which make you breathe hard enough that it is difficult to talk and your heart beats really fast. It would be hard to hold a conversation during vigorous activity. Activities include: stair machine or elliptical at a fast pace, jogging or running, race walking, singles tennis, cycling at a fast pace (> 10 mph), or steady, lap swimming.

1. In the last 3 months, on average, what vigorous activities do you do in a typical week?
    a. Activity 1: [record type and duration]
    b. Activity 2: [record type and duration]
    c. Activity 3: [record type and duration]

d. Activity 4: [record type and duration]
e. Activity 5: [record type and duration]
f. Activity 6: [record type and duration]
g. Activity 7: [record type and duration]

Next, I am going to ask you about moderate activities, which make you breathe hard enough that it is difficult to whistle or sing, and your heart beats a little faster. You would still be able to have a conversation during moderate activity. Activities include: brisk walking, aerobics, elliptical at comfortable pace, doubles tennis, gentle swimming, cycling at a moderate pace, recreational dancing, or weight training.

2. In the last 3 months, on average, what moderate activities do you do in a typical week?
   a. Activity 1: [record type and duration]
   b. Activity 2: [record type and duration]
   c. Activity 3: [record type and duration]
   d. Activity 4: [record type and duration]
   e. Activity 5: [record type and duration]
   f. Activity 6: [record type and duration]
   g. Activity 7: [record type and duration]

Eligibility calculation:
If vigorous activity minutes + (moderate activity minutes/2) over 75 minutes per week **– INELIGIBLE**
If vigorous activity minutes + (moderate activity minutes/2) under 75 minutes per week **– ELIGIBLE**

If eligible: Based on these questions you are eligible to continue in the study. If you are interested in participating in this study, I will send you an email with the link to schedule your two-hour session at a time convenient for you. I will also send you some restrictions we ask of all participants in preparation for the session, such as abstaining from vigorous physical activity or tobacco products before the session. Is it okay to send this email to you?

If not eligible: Thank you for your interest in our study. Unfortunately, you are not eligible to continue, but we appreciate your time and have a great day.

Appendix B Demographic and Health Behavior Questions

Instructions**:** Please provide the following information.
1. Age2. Date of Birth3. Sex
__________ / _____ / _________ Female
(month / day / year)_____ Male

4. What year are you in undergraduate college? ___________

5. I identify my race or ethnicity as: (please select all that apply)
___(1) American Indian/Alaska Native
___(2) Asian
___(3) Native Hawaiian or other Pacific Islander
___(4) Black or African American
___(5) White
___(6) Bi- or multiracial, please specify: ___________________
___(7) Other, please specify: _____________________________
___(8) Unknown

6. Are you of Hispanic or Latino descent?
___(1) Yes
___(2) No

7. Do you currently live on campus?
___Yes; I have [# of roommates] _______________________________________
___No; I live:
Off campus
At home.
Other: _______________

8. Are you currently employed either full or part-time?
___ Yes
___ No

9. Do you engage in overnight or shift-work?
___Yes; My job and typical hours (e.g., 11pm–7am) are: ______________________
___No

10. Are you currently taking medications for **mental health** purposes?
___Yes; I take ____
___No

11. Are you currently taking medications for any **physical health** conditions?

___Yes; I take ____

___No

For Women only:

12. Are you currently taking **birth control pills** or any other form of **hormonal contraceptives** (e.g., intrauterine device [IUD], implant, shot, patch)?

___Yes; I take/have: _______________________________________

___No

For Women only:

13a. What was the first day of your most recent menstrual period? For your convenience, you may refer to the calendar next to the computer.

13b. What is your typical cycle length (e.g., 28 days)

14. Have either of your biological parents ever had a heart condition or stroke?

___ Yes

___ No

___ Don't know

___ Refused

15. Have either of your biological parents ever had high blood pressure or taken high blood pressure medications?

___ Yes

___ No

___ Don't know

___ Refused

16. During the past 30 days, on how many days did you **smoke cigarettes**?

A. 0 days
B. 1 or 2 days
C. 3 to 5 days
D. 6 to 9 days
E. 10 to 19 days
F. 20 to 29 days
G. All 30 days

17. During the past 30 days, on how many days did you **use e-cigarettes (e.g., vapig, Juul)**?

A. 0 days
B. 1 or 2 days
C. 3 to 5 days
D. 6 to 9 days
E. 10 to 19 days
F. 20 to 29 days
G. All 30 days

18. During the past 30 days, on how many days did you have at least one drink of **alcohol**?

A. 0 days
E. 10 to 19 days

B. 1 or 2 days

C. 3 to 5 days

D. 6 to 9 days

F. 20 to 29 days

G. All 30 days

19. During the past 30 days, how many times did you use **marijuana**?

A. 0 days

B. 1 or 2 days

C. 3 to 5 days

D. 6 to 9 days

E. 10 to 19 days

F. 20 to 29 days

G. All 30 days

20. Approximately what time did you wake up today?
[hour/minute]

21. Approximately how many hours of sleep did you get last night?
[hour/minute]

Appendix C The Activation-Deactivation Adjective Check List (AD ACL)

This scale consists of a number of words that describe different feelings and moods. Please use the rating scale next to each word to describe your feelings *at this moment*. Work rapidly, but please mark all the words. Your first reaction is best.

1	Active	Definitely	Slightly	Does not apply/unsure	Definitely not
2	Placid	Definitely	Slightly	Does not apply/unsure	Definitely not
3	Sleepy	Definitely	Slightly	Does not apply/unsure	Definitely not
4	Jittery	Definitely	Slightly	Does not apply/unsure	Definitely not
5	Energetic	Definitely	Slightly	Does not apply/unsure	Definitely not
6	Intense	Definitely	Slightly	Does not apply/unsure	Definitely not
7	Calm	Definitely	Slightly	Does not apply/unsure	Definitely not
8	Tired	Definitely	Slightly	Does not apply/unsure	Definitely not
9	Vigorous	Definitely	Slightly	Does not apply/unsure	Definitely not
10	At Rest	Definitely	Slightly	Does not apply/unsure	Definitely not
11	Drowsy	Definitely	Slightly	Does not apply/unsure	Definitely not
12	Fearful	Definitely	Slightly	Does not apply/unsure	Definitely not
13	Lively	Definitely	Slightly	Does not apply/unsure	Definitely not
14	Still	Definitely	Slightly	Does not apply/unsure	Definitely not
15	Wide Awake	Definitely	Slightly	Does not apply/unsure	Definitely not

16	Clutched Up	Definitely	Slightly	Does not apply/unsure	Definitely not
17	Quiet	Definitely	Slightly	Does not apply/unsure	Definitely not
18	Full of Pep	Definitely	Slightly	Does not apply/unsure	Definitely not
19	Tense	Definitely	Slightly	Does not apply/unsure	Definitely not
20	Wakeful	Definitely	Slightly	Does not apply/unsure	Definitely not

Appendix D Paffenbarger Physical Activity Questionnaire

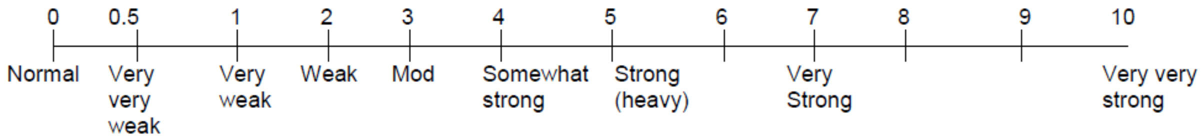
In the past week.

1.How many city blocks or their equivalent do you normally walk each day?
    a.[enter blocks/day] (12 blocks = 1 mile)
2.What is your usual pace of walking? Please select one.
    a.Casual or strolling (less than 2 mph)
    b.Average or normal (2 to 3 mph)
    c.Fairly brisk (3 to 4 mph)
    d.Brisk or striding (4 mph or faster)
3.How many flights of stairs do you climb up each day?
    a.[enter Flights/day] (1 flight = 10 steps)
4.List any sports or recreation that you have actively participated in during the past week.

	Sport, recreation, or other physical activity	Number of per week	Average time per episode		Rating (light, mod, heavy)
			Hours	Minutes	
1					
2					
3					
4					
5					

5.Which of these statements best expresses your view? Please select one.
    a.I get enough exercise to keep healthy.
    b.I should get more exercise
    c.Don't know
6.At least once a week, do you engage in regular activity such as brisk walking, jogging, bicycling, swimming, etc. long enough to work up a sweat, get your heart humping, or get out of breath?
    a.Yes
        i.How many times per week? __________
        ii.Activity: ________________
    b.No

7.When you are exercising in your usual fashion, how would you rate your level of exertion (degree of effort)? Please circle one number.
8.



Appendix E Sedentary Behavior Questionnaire

On a typical WEEKDAY, how much time do you spend (from when you wake up until you go to bed) doing the following? Please check one answer per question.

Note that text in red have been added to be more relevant to a college-aged sample. Black strikethrough text reflect deleted text.

1	Sitting while watching television (including online videos ~~on VCR/DVD~~)	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
2	Sitting while using the computer for non-school or non-work activities or playing video games	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
3	Sitting and working without a computer (studying with a textbook) ~~while doing non-computer office work or paperwork not related to your job (paying bills, etc.)~~	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
4	Sitting listening to music, reading a book or magazine recreationally, or doing arts and crafts	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
5	Sitting and talking on the phone or texting	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
6	Sitting in a car, bus, train, or other mode of transportation	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs

On a typical WEEKEND, how much time do you spend (from when you wake up until you go to bed) doing the following? Please check one answer per question.

7	Sitting while watching television (including online videos ~~on VCR/DVD~~)	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
8	Sitting while using the computer for non-school or non-work activities or playing video games	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
9	Sitting and working without a computer (studying with a textbook) ~~while doing non-computer office work or paperwork not related to your job (paying bills, etc.)~~	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
10	Sitting listening to music, reading a book or magazine recreationally, or doing arts and crafts	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
11	Sitting and talking on the phone or texting	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs
12	Sitting in a car, bus, train, or other mode of transportation	None	15 min or less	30 min	1 hr	2 hrs	3 hrs	4 hrs	5 hrs	6 hrs

Appendix F PANAS

This scale consists of a number of words that describe different feelings and emotions. Please rate the following items in terms of how descriptive they are of you. Indicate to what extent you generally feel this way...

	Interested	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
2	Distressed	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
3	Excited	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
4	Upset	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
5	Strong	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
6	Guilty	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
7	Scared	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
8	Hostile	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
9	Enthusiastic	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
10	Proud	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
11	Irritable	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely

12	Alert	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
13	Ashamed	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
14	Inspired	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
15	Nervous	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
16	Determined	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
17	Attentive	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
18	Jittery	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
19	Active	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely
20	Afraid	Very slightly or not at all	A little	Moderately	Quite a bit	All the time/ extremely

Appendix G Perceived Stress Scale (PSS)

<u>Instructions</u>: The questions in this scale ask you about your feelings and thoughts during the last month. In each case, please indicate how often you felt or thought a certain way.

1	In the last month, how often have you been upset because of something that happened unexpectedly?	Never	Almost Never	Sometimes	Fairly Often	Very Often
2	In the last month, how often have you felt that you were unable to control the important things in your life?.	Never	Almost Never	Sometimes	Fairly Often	Very Often
3	In the last month, how often have you felt confident about your ability to handle your personal problems?	Never	Almost Never	Sometimes	Fairly Often	Very Often
4	In the last month, how often have you felt nervous and "stressed?"	Never	Almost Never	Sometimes	Fairly Often	Very Often
5	In the last month, how often have you felt that things were going your way?	Never	Almost Never	Sometimes	Fairly Often	Very Often
6	In the last month, how often have you found that you could not cope with all the things that you had to do?	Never	Almost Never	Sometimes	Fairly Often	Very Often
7	In the last month, how often have you been able to control irritations in your life?	Never	Almost Never	Sometimes	Fairly Often	Very Often
8	In the last month, how often have you felt that you were on top of things? (1)	Never	Almost Never	Sometimes	Fairly Often	Very Often
9	In the last month, how often have you been angered because of things that were outside your control?	Never	Almost Never	Sometimes	Fairly Often	Very Often
10	In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?	Never	Almost Never	Sometimes	Fairly Often	Very Often

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