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Physical Activity and Depressive Symptoms in Adolescence: Direction of Effects and Mechanisms of Influence

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Physical Activity and Depressive Symptoms in Adolescence: Direction of Effects and Mechanisms of Influence

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Abstract

Physical activity (PA) is associated with numerous physical and mental health benefits, such as decreased rates of cardiovascular disease and depression. Stress-response systems may play an important role in this relationship as PA has been shown to cause adaptations to both physiological and psychological stress systems. Less is known about the short and long-term effects of PA on depressive symptoms in adolescents even though adolescence marks an important period of development with regard to changes in rates of depression and physical activity. The objectives of this study were to evaluate concurrent and prospective associations of PA on depressive symptoms in adolescence and associated mechanisms of influence. One hundred eighty-seven urban high school students (11-18 years old; 84% racial/ethnic minority) completed stress interviews and mood questionnaires at time 1, followed by 5 days of salivary cortisol samples and daily diary reports on PA, mood, and stressors. Participants returned 6-9 months later (time 2) to complete additional stress interviews and mood questionnaires. Multilevel models were used to estimate within- and between-person associations of daily PA with cortisol patterns and mood over time, as well as potential moderators and mediators. Youth who engaged in more daily PA on average, reported fewer negative mood symptoms and exhibited lower cortisol area under the curve (AUC) on average compared to less active counterparts. Same day and previous day PA predicted fewer self-reported negative mood symptoms. Coping self-efficacy was a significant mediator between daily PA and negative mood for girls, but not boys. Gender also moderated prospective associations between PA and depressive symptoms, such that for males there was a significant positive relationship between time 1 PA and time 2 depressive

symptoms, whereas for females, the relationship was nonsignificant. Findings provide evidence of concurrent and prospective associations between PA and depressive symptoms in adolescence.

Physical Activity and Depressive Symptoms in Adolescence: Direction of Effects and Mechanisms of Influence

Regular physical activity—defined by current U.S. guidelines as "at least 60 minutes of moderate-to-vigorous physical activity per day" for youth ages 6 through 17, is associated with improved health outcomes across the lifespan (2018 Physical Activity Guidelines Advisory Committee, 2018). Physical health benefits (e.g., lower risk of all-cause mortality, lower rates of cancer, decreased risk for cardiovascular and metabolic disease, lower rates of obesity, and improved physical functioning) associated with engaging in regular physical activity are abundant and well documented (for reviews, see (Janssen & LeBlanc, 2010; Warburton et al., 2006). Over recent years, researchers have also garnered increasing evidence for mental health benefits (e.g., improved cognitive functioning, reduced anxiety, decreased depression) associated with physical activity (Donnelly et al., 2016; Harvey et al., 2010; Ströhle, 2009). Regarding depression, evidence supporting the benefits of physical activity has been particularly compelling. Yet, despite the numerous physical and mental health benefits associated with physical activity, current data suggest that only 16.5% of U.S. adolescents meet the current physical activity guidelines (CDC, 2019). These numbers suggest physical activity may currently be an untapped resource for improving mental health outcomes – particularly depression– among adolescents.

Understanding relationships between physical activity and depression in adolescence is critical, as changes in patterns of both physical activity and depression occur during this developmental period. As youth progress into adolescence, physical activity levels often decrease– especially among girls (Brodersen et al., 2007). At the

same time, the adolescent transition is also associated with increases in rates of depression (Avenevoli et al., 2015), as well as the emergence of gender differences in depression –with girls more likely to develop depression than boys (Thapar et al., 2012). Moreover, these patterns often persist into adulthood; depressed teens are more likely to experience depression as adults, and active teens are more likely to become physically active adults (Fergusson & Woodward, 2002; Trudeau et al., 2004). The adult literature has provided much evidence for the benefits of physical activity in both reducing and preventing symptoms of depression (e.g., Carek et al., 2011; Conn, 2010; Rosenbaum et al., 2014). Accumulating evidence suggests a similar relationship among adolescents (e.g., Bailey et al., 2018; Brown et al., 2013); however, the underlying mechanisms remain unclear. Due to the unique biological and psychosocial changes that occur during adolescence, it is important to understand how the effects of physical activity function during this critical period of development.

Physical Activity and Depression

The literature review will begin with an overview of findings from cross-sectional studies which have been helpful in establishing concurrent associations between PA and depression. Next, the longitudinal literature will be discussed to review extant knowledge on prospective associations and direction of effects. Finally, outcomes from PA interventions will be reviewed as they have helped clarify the temporal order of effects by demonstrating how outcomes such as depression are impacted by increases in PA.

Cross-Sectional Associations

Cross-sectional studies have found an inverse association between physical activity (PA) and depressive symptoms in adolescents (Asare & Danquah, 2015; Cao et

al., 2011; Kremer et al., 2014; Prasad et al., 2009; Wiles et al., 2012). In fact, one study found that for each additional hour of PA per week, there was an 8% decrease in adolescent-reported depressive symptoms (Rothon et al., 2010). Despite accumulating evidence suggesting PA is associated with fewer concurrent symptoms of depression, differences in sample characteristics and measurement inconsistency have led to varied outcomes in some studies.

Group differences have been reported with regard to gender and social economic status (SES). For instance, Catillo et al. (2014) found an inverse association between self-reported depressive symptoms and PA for boys, but not girls, in a school-based study of 1,508 adolescents. A meta-analysis by Korczak et al. (2017), reported weaker effect sizes in high social risk (e.g., low income, minority status) samples. However, as the authors acknowledged, few studies to date have examined associations between PA and depression in high-social risk adolescent samples, therefore results should be interpreted with caution until additional research is conducted in these populations (Korczak et al., 2017).

The method and metric by which studies have measured PA has further limited interpretability of findings. Studies using validated self-report measures of PA have shown stronger effect sizes compared to those using non-validated measures (Korczak et al., 2017). For example, Hoare et al., (2016) found no association between self-reported PA and depressive symptoms but acknowledged study methods for estimating PA may have led to some measurement error in that the adolescents were categorized into high, medium, low, and inactive depending only on their self-reported activities on the last school day. In a study that used both objective (accelerometry) and subjective (self-

report) methods to measure PA in a community sample of 15-16 year-olds, more frequent self-reported vigorous PA (≥4x/week) was associated with fewer symptoms of depression; however, there were no significant associations between objectively measured PA and any mental health outcome (Hrafnkelsdottir et al., 2018). Overall, these cross-sectional studies have been useful in establishing an association between PA and depression, however, they cannot control for bi-directional relationships and are unable to prove causality, thus the longitudinal research will be examined as well.

Longitudinal Associations

Extant evidence from prospective studies suggests that PA may not only reduce current depressive symptoms but also decrease the risk of developing depression in the future. According to a systematic review of prospective-based studies measuring relationships between PA (i.e., aerobic) and depression, 25 out of 30 studies reviewed found that PA was negatively associated with risk of depression at follow-up (Mammen & Faulkner, 2013). However, the wide age range of subjects (11-100 years), varying follow up intervals (1-27 years), and heterogeneity in PA and depression measurement limit the interpretability of Mammen and Faulker's findings. In studies specific to youth (i.e., under 18), there is strong evidence for PA and decreased current depressive symptoms, but weaker evidence for the association with future depressive symptoms (Korczal et al., 2017). Unfortunately, there is a paucity of research explicitly focused on adolescents, rather than child and adolescent samples combined, so effects specific to adolescents remain unclear.

The few prospective studies to examine the relationship between PA and depression among adolescents have yielded mixed results. There is evidence that higher

levels of PA in mid-adolescence are associated with lower levels of depression, and slower increases in depression symptoms through emerging adulthood (McPhie & Rawana, 2012). For example, (Jerstad et al., 2010) found that adolescent girls' PA significantly reduced the risk for future increases in depressive symptoms and risk for the onset of depression over a 6-year period. Findings from several other studies examining this relationship over varying time periods further support the idea that PA may play a role in preventing future depression (Motl et al., 2004; Sund et al., 2011). In contrast, other studies have found no longitudinal association between adolescent PA (when measured objectively) and the development of depressive symptoms (Toseeb et al., 2014). While measurement inconsistencies highlighted earlier likely account for some of these mixed findings, prospective outcomes have also varied by *type* of depression symptoms. For example, two studies (Stavrakakis et al., 2012; Booi et al., 2015) found that PA was prospectively and inversely related to affective, but not somatic symptoms of depression among adolescents. Given the inconsistent results and smaller effect sizes associated with these prospective studies, additional research is needed to confirm findings.

One explanation for smaller effect sizes found in studies using longitudinal compared to cross-sectional designs may be related to directionality. An inherent limitation of cross-sectional designs is the inability to determine a temporal order between variables. As such, cross-sectional studies have been unable to determine the direction of effects, that is: are adolescents who participate in PA less likely to have depressive symptoms, or are adolescents with increased depressive symptoms less likely to participate in PA? Considering that many of the physical (e.g., lack of energy,

disturbed sleep, slowed movement, etc.) and psychological (e.g., low self-esteem, low motivation, anhedonia, etc.) symptoms of depression likely influence an individual's motivation for — and ability to engage in — PA, both directions are possible. In order to clarify the direction of effects, additional prospective studies should test the relation between PA and depressive symptoms over time as there is accumulating evidence suggesting the relationship may be bidirectional.

Of the four studies to explicitly test for bidirectional effects, support was found in all but one study and effects were stronger for girls than for boys. Neissaar and Raudsepp (2016) examined changes in PA and depressive symptoms in urban adolescent girls over a two-year period and found that initial level as well as changes in PA participation were inversely related to depressive symptoms over time; moreover, depressive symptoms significantly reduced future PA. In line with Neissar and Raudsepp's findings, Jerstad and colleagues (2010) reported that depressive symptoms significantly reduced future PA levels among adolescent girls. Additional work by Stavrakakis et al. (2012) used structural equation modeling to examine bidirectional effects of PA and depressive symptoms in 2,230 adolescents measured at three time points between age 10 and 17. They found relatively weak but significant cross-lagged paths from prior physical activity to later depression, as well as from prior depression to later PA (βs = -.039 to -.047) but did not test for gender differences (Stavrakakis et al.,2012). In contrast, Birkeland et al., (2009) found no evidence for a bidirectional relationship between PA and adolescent depressive symptoms.

Overall, insufficient evidence is available because of a small number of prospective studies with mixed results. Additional prospective studies are needed to test

for reciprocal relationships and/or alternate directions of effects over time. It is also unclear how this association functions across time. For example, what is the time period between physical activity and future effects on mental health? In order to inform optimal windows for intervention, future studies should incorporate both short-term (daily) and long-term (yearly) measurement intervals to characterize effects throughout the day and over time.

Intervention Outcomes

Intervention studies have added to the literature on underlying processes and direction of effects by temporally demonstrating how outcomes such as depression are impacted by increases in PA. Among adults, PA interventions have demonstrated positive treatment outcomes, such as reduced depressive symptoms and improved mood (ann het Rot et al., 2009; Bailey et al., 2018; Biddle & Asare, 2011; Korczak et al., 2017; Lubans et al., 2016; Radovic et al., 2017; Rosenbaum et al., 2014). In fact, some PA interventions have shown significant treatment effects comparable to psychotherapy and psychopharmacology interventions (Blumenthal et al., 2007; Dinas et al., 2011; Kvam et al., 2016).

Fewer interventions have been conducted among adolescents and variations in type and dose of PA used in interventions (e.g., aerobic vs. anaerobic, group vs. individual, etc.) make it difficult to compare treatment outcomes. The majority of interventions have been supervised, aerobic, and group-based (Bailey et al., 2017); and a few have consisted of sports participation (Eime et al., 2013). Considering larger effect sizes have been found in unsupervised (vs. supervised) PA interventions for adults (Conn, 2010), future studies should also examine unsupervised PA interventions among

adolescents. At this point, the most effective interventions for youth appear to include aerobic and resistance-based activity of moderate-to-vigorous intensity engaged in multiple times per week over at least 7-8 weeks (Bailey et al., 2018; Carter et al., 2016). However, there is also evidence that even small increases (e.g., 60-90 min per week) in any type of PA can reduce adolescent depressive symptoms (Janssen & LeBlanc, 2010). Two recent meta-analyses found PA interventions were effective in reducing depressive symptoms among adolescents with depression (Carter et al., 2016; Bailey et al., 2017). Interestingly, the effect sizes in these studies did not differ by intensity of PA or type of PA, further suggesting that all PA may be beneficial in reducing symptoms of depression.

A remaining question is in what groups of adolescents is PA effective in reducing depression? Similar to the adult literature, there is evidence that PA reduces depressive symptoms in both clinical (Radovic et al., 2017) and non-clinical (Carter et al., 2016) populations of youth, though some researchers found stronger effect sizes in clinical samples compared to non-clinical samples (Carter et al., 2016). There is also evidence of stronger treatment effects for girls compared to boys (Korczak et al., 2017). Overall, moderator analysis has been limited by the small number of interventions focused on adolescents and highlights the need for additional research to inform and refine intervention methods.

Stress Pathways Linking Physical Activity and Depression

So far, the pathways and processes underlying the relationship between physical activity and improved mental health outcomes remain unclear. A notable and consistent finding emerging from both the adult and the adolescent literatures is that the impact of physical activity on depression is not related to changes in fitness level (Chu et al., n.d.;

Zschucke et al., 2013a). Thus, if change in fitness level does not mediate the observed reduction in symptoms, then what other mechanism(s) might be implicated? Evidence suggests that several processes may be involved in this relationship, including biological processes (e.g., neuroendocrine response, neuroplasticity, inflammation; (Brunoni et al., 2008; Ernst et al., 2006; Nabkasorn et al., 2006; Schuch et al., 2016) and psychological processes (e.g., mood and affect regulation, self-esteem, social support, self-efficacy; (Bernstein & McNally, 2018; McAuley et al., 2000; Reed & Ones, 2006). Stress response systems are of particular interest given known links between stress and depression (Lee, et al., 2010) and accumulating evidence that PA can cause adaptations to biological and psychological stress response systems. Therefore, the current study used Salmon's Stress-Adaptation model as a theoretical framework through which to examine the effects of physical activity on adolescent depression.

Salmon's Stress-Adaptation model provides a useful framework for examining the effects of PA on adolescent depression as it highlights the interconnectedness of stress response systems and their impact on physical and mental health. An important tenet of this theory is that PA is associated with changes to stress response systems- both biological and psychological (Salmon, 2001). Thus, PA may represent a type of response inhibition mechanism, by which one can essentially become more resistant to stress. In other words, repeatedly engaging in controllable physical stressors (i.e., PA) leads to adaptations in reactivity and/or recovery to other physical and psychological life stressors. Consistent with this supposition, PA has been found to influence several major stress systems through a network of interacting biological (e.g., neuroendocrine) and psychological (e.g., mood and affect) mechanisms in adolescents (Reed & Ones, 2006;

Traustadóttir et al., 2005). As such, it may lead to a more adaptive calibration of stress responses to life events and daily hassles. The proposed study will examine two biological and psychological stress processes to determine whether they explain the physical activity-depression link.

Biological Stress Processes

Biological stress response systems may play a role in explaining the relationship between PA and mood. One mechanism is through the hypothalamic-pituitary-adrenal (HPA) axis. The HPA axis and its main byproduct, cortisol, play a critical role in promoting adaptive responses to stressors. Moreover, PA can have acute and chronic effects on cortisol levels, which may help regulate physical and psychological stress response. Considering that HPA dysfunction has consistently been found in individuals with stress-related mood disorders, such as depression (Pariante & Lightman, 2008), the current study sought to explore whether cortisol is involved in the relationship between PA and depression in adolescence.

Acute cortisol effects. Regarding acute cortisol stress response, heightened cortisol reactivity and delayed recovery are most associated with depressive symptoms among adolescents. Interestingly, acute PA is also associated with short term increases in cortisol. This increase in cortisol is thought to be a physiological response to the physical stress of PA, helping the body respond to the increased energy demands (Hill et al., 2008). However, regular PA is associated with attenuated cortisol production in response to subsequent PA. Considering Salmon's stress-adaptation model and other theories of cross-stressor adaptation (Sothman et al., 1996), regular PA might also lead to physiological adaptations to the HPA axis in response to psychological stress. Evidence

to support this theory can be found in several studies showing that adults who engage in regular PA show reduced neuroendocrine response to not only physical stressors (PA) but also psychological stressors (e.g., social evaluation) compared to less active adults (Forcier et al., 2006). For example, a randomized control trial among young men found that individuals with higher aerobic fitness showed significantly less cortisol response to a laboratory stress task (i.e., Montreol Imaging Stress Task) compared to sedentary individuals (Zschucke et al., 2015). Very few studies have explicitly tested this association among youth, however there is preliminary evidence of stress-buffering effects of PA in children (Zschucke et al., 2013b). Altogether, these findings suggest regular PA may help regulate neuroendocrine activity through physiological adaptations to the HPA axis, resulting in attenuated cortisol release (Brumby et al., 2013).

Diurnal cortisol rhythms. The relationship between PA and diurnal cortisol patterns is more unclear. Diurnal cortisol rhythms refer to the normal patterns of changes in cortisol levels occurring throughout the day and are associated with stress and health outcomes (see Adam & Kumari 2009, for review). Typically, cortisol peaks in the morning and gradually decreases throughout the day – a pattern that is thought to prepare the body to meet environmental demands throughout the day. The cortisol awakening response (CAR) occurs in the 30-45 minutes after awakening and usually returns to baseline levels within 60 minutes. However, individuals with depression often show a shift in this pattern such that cortisol levels peak in the evening (Bhagwagar et al., 2005; Birmaher & Heydl, 2001). Another parameter (diurnal slope) characterizes the rate of cortisol decline throughout the day. Flatter diurnal cortisol slopes are associated with adolescent depression (Doane et al., 2013). Area under the curve (AUC) is a cortisol

parameter which represents the total amount of cortisol output over the day. Elevated day time cortisol has been associated with high levels of stress (Chida & Steptoe, 2009) and depression (Pariante & Lightman, 2008), while regular physical activity (McHale et al., 2012) is associated with lower cortisol levels over the day.

Despite the known associations between diurnal cortisol patterns, stress, and depression, few studies have examined the effects of PA on diurnal cortisol rhythms. Drawing from the adult literature, a four-month PA intervention found that increased PA was associated with improved CAR among chronically stressed adult caregivers (Urizar et al., 2010). Another study found that 8 weeks of moderate PA led to a reduction in depressive symptoms and 24-hour cortisol secretion (i.e., cortisol AUC) among women with depression (Nabkasorn et al., 2006) . Unfortunately, little is known about the effects of PA on adolescent diurnal cortisol patterns. Considering previous findings of gender differences in CAR (ie., girls > boys), as well as evidence for steeper slopes and reduced CAR in adolescents, additional research is needed to understand how PA levels influence diurnal cortisol profiles during this critical period of development.

Psychological Stress Processes

Mood and affect. PA has been shown to influence mood through both direct and indirect pathways. There is ample evidence that PA can directly elevate mood by increasing positive affect (Stavrakakis et al., 2015) as well as decreasing negative affect (Biddle & Ekkekakis, 2012). In addition to directly altering mood, regular PA may also indirectly alter mood by altering the way individuals respond to stressors. There is growing evidence of acute and cumulative benefits of PA on coping with stress (Edwards, 2006; Puterman et al., 2011a). As previous research has demonstrated

accumulated effects of high emotional reactivity to stress increases risk for mood disorders (Booij et al., 2018), affect regulation may be another pathway through which PA reduces depression.

Regarding the cumulative benefits of PA, research questions have focused on whether physically active individuals react to and/or recover from stressors differently than less active individuals. Differences for both affective reactivity and recovery are well documented (Bernstein & McNally 2018) and have been found across laboratory and naturalistic settings. For example, compared to sedentary individuals, physically active individuals show smaller increases in negative mood (Klaperski et al., 2013) as well as smaller declines in positive mood (Childs & de Wit, 2014) in response to laboratory based social stressors. Extending the ecological validity of these findings, Dunton et al., 2014 demonstrated that physically active children (ages 9-13) show higher stability in positive and negative affect within the context of everyday life. Moreover, Puterman et al. (2017) showed that adults who regularly engaged in daily PA have reduced negative affect response to daily stressful events. The studies above provide support for health-protective mechanisms of PA via affect regulation. That is, if reactivity to stress is influenced by activity levels, engaging in regular PA may be one way to protect against the negative effects of stress (Hamer et al., 2012).

PA interventions have provided additional support and shed light on the direction of effects by showing how increases PA is associated with changes in affective reactivity among previously inactive individuals. For example, Von Haaren and colleagues (2015) investigated the effects of a 20-week aerobic exercise intervention on stress response among sedentary– though otherwise healthy– college students. Compared to the control

group, students who participated in the PA intervention showed reduced emotional reactivity (i.e., negative affect response) to real-life academic stressors, particularly under conditions of high perceived stress. The authors concluded their PA intervention reduced stress reactivity by increasing participants' perceived self-control, even in situations of severe stress (von Haaren et al., 2015). Very few interventions have targeted this relationship among adolescents, however, an early study by Norris and colleagues (1992) assigned adolescents to either high or moderate intensity aerobic training, flexibility training or a control group meeting twice a week for 10 weeks and found that the relationship between stress and negative mood significantly reduced for the high intensity group at the end of the training period. Of note, the relationship between stress and negative mood was strengthened for participants assigned to the less active groups in this study. Altogether, these results could have important implications for youth exposed to high levels of stress, particularly those who do not meet current physical activity guidelines.

Acute benefits of PA on affective reactivity have also been found across several settings and populations, though the majority of research to date has focused on acute effects for adults within laboratory settings. For example, Bernstein and McNally (2018) found evidence that just a single session of exercise protected against acute emotion dysregulation and improved emotional recovery following a public speaking stressor among adults at various risk for depression. Another laboratory study showed that depressed adults given an opportunity to exercise before a negative mood induction task displayed attenuated affective responses – similar to the non-depressed participants (Mata et al., 2013). Conversely, the depressed participants who did not engage in PA prior to

the mood induction task showed elevated negative affect responses. Among children, one school-based study found that third and fourth graders demonstrated a significant reduction in negative affect after playing just a single bout of an active video game (Lee et al., 2017).

Although fewer studies have examined acute effects in real life settings, results are generally in line with laboratory-based findings. For example, one study found that negative affect reactivity was reduced by 17% on days that adults reported a bout of PA compared to days without PA, independent of their general PA level (Puterman et al., 2017). Additionally, this study helped inform timing of effects by showing that among underactive adults, negative affect response to a given stressor was reduced the closer in time that stressor occurred to the bout of exercise. Another study investigated the stress-buffering effects of various health behaviors on affect within the context of college students' everyday life stressors and found the relationship between stress and affect (both positive and negative) significantly weakened on days when participants were more physically active than usual (Flueckiger et al., 2016). Altogether, these findings highlight the utility in examining within-person, in addition to between-person, differences at the daily level.

Moreover, there is reason to believe that PA and stress have reciprocal relationships and influence each other- much like PA and depression. For example, higher levels of perceived stress are related to lower levels of PA (Geulayov et al., 2010; Stults-Kolehmainen & Sinha, 2014). Another study demonstrated physically inactive youth were stressed at a higher level than their physically active peers (Gerber et al., 2017). However, the cross-sectional study design did not allow the researchers to test the

direction of effects- that is, does PA buffer the effects of stress or do individuals with high stress participate in less physical activity? Therefore, the current study aimed to clarify the direction of effects by examining same day as well as lagged relationships.

Coping Self-efficacy. Coping self-efficacy refers to confidence in one's ability to successfully handle stressful situations and emotions (Chesney et al., 2006) and is positively associated with PA (Blaydon & Birch, 2007) among adolescents. For example, several adolescent studies have found that regular exercisers report higher coping self-efficacy and perceived ability to cope with negative mood and stress compared to their less active peers (Kishida, 2015; Mata et al., 2013). Participating in PA is thought to enhance coping self-efficacy in several ways, such as: increasing self-esteem, providing a sense of accomplishment and/or mastery, and serving as an effective coping strategy to handle stress. Of note, these same constructs are active components in several effective treatments for depression. For example, behavioral activation, a common treatment approach for depression, includes activity scheduling interventions which target increasing pleasant and mastery experiences as well as physical activity (Dimidjian et al., 2011).

Indeed, several studies have shown associations between coping self-efficacy and depression among adolescents (Muris, 2002; Caprara et al., 2010), such that higher levels of coping self-efficacy are generally associated with reduced symptoms of depression (Shields et al., 2010). Additionally, coping self-efficacy has been found to mediate the relationship between stress and depression in children (Singh & Bussey, 2011) adolescents, (Trompeter et al., 2018), and young adults (Sawatzky et al., 2012) . As such,

coping self-efficacy may represent another possible mediator between PA and depression.

Surprisingly little research has examined relationships between changes in PA, coping self-efficacy, and depression, especially among adolescents. One study by (Oddie et al., 2014) assessed the effects of a PA program on coping self-efficacy, depression, and motivation to exercise in a small (N = 35) sample of Canadian youth (ages 10 -17) who were already receiving services at a community mental health center. They reported significant improvement in participants' coping ability as well as a significant reduction in depression symptoms following the 8-week program. However, the limitations related to sample and measurement characteristics limit interpretability and generalizability of findings. For example, this study only measured youth-reported coping self-efficacy every four weeks and thus ignored potential dynamic relationships that may exist between PA, coping self-efficacy, and depressive symptoms.

Overreliance on measuring coping self-efficacy as a static trait is a major limitation of the current literature and contradicts Bandura's (1986) emphasis on self-efficacy interacting with environmental influences in a dynamic fashion. Examining coping self-efficacy as labile state-like characteristics and in concert with fluctuations in PA and mood is critical to understanding its role as a potential mediator in the PA–depression link. Studies that take a more microanalytic approach – such as examining how day-to-day variations in PA relate to changes in coping self-efficacy and mood are clearly needed to overcome the limitations of prior research and provide better insight into the causal direction of associations. Therefore, the current study chose an intensive longitudinal design (daily diary study) which allowed us to capture day-to-day

information on relationships between study variables within the context of adolescents' natural environments.

Overall, there is considerable evidence that physical activity alters numerous systems throughout the body and brain. As such, effects on mental health most likely arise through a combination of multiple interacting biological and psychological pathways (Lees & Hopkins, 2013; Moylan et al., 2013; Bernstein & McNally, 2018). However, very few studies have measured both biological and psychological stress systems when examining short and long-term interrelations between physical activity and depression over adolescence.

Rationale

Associations between physical activity and stress-induced mental health outcomes over adolescence remain unclear in large part because of the salient limitations of current research. Therefore, the current study sought to address the limitations outlined below.

First, few studies have examined both within-person and between-person associations between PA and adolescent depression. Research to date has overly relied on between-subject designs which ignores potential dynamic relationships that may exist between PA and various affective and biological states. Between-person effects (e.g., how people differ from each other) are only one piece of the puzzle and cannot be generalized to the individual level (e.g., how people change relative to themselves), so it's important to measure both at the same time. In order to advance understanding of how these processes and relationships unfold in adolescence, the current study incorporated an intensive repeated measures design which allowed us to distinguish within-person and between-person effects. Moreover, little research has examined

differences at the daily level (daily diary) versus longer (survey) periods of time. Given the previously discussed conflicting findings regarding the relationship between PA and concurrent versus future symptoms, the current study examined both short- and long-term intervals in order to provide a more nuanced understanding of this dynamic relationship across time.

Second, despite evidence for PA altering several biological and psychological stress pathways, few studies have measured both stress systems in parallel. Research that integrates these previously disparate lines of research will facilitate comparison of effects and allow researchers to uncover potential interactions. Therefore, the current study examined biological and psychological stress pathways simultaneously in relation to PA and adolescent depression.

Third, the ecological validity of stressor measurement needs further consideration. While laboratory-based tasks may reliably elicit stress responses, they do not tell us whether PA is associated with biological or psychological reactivity to naturalistic stressors. Understanding how PA in everyday life may contribute to variability in biological and psychological stress pathways is critical to understanding mental health benefits of PA. To maximize ecological validity, we used daily diaries and diurnal cortisol sampling to measure daily dynamics of PA and mood as well as biological stress processes within participants naturalistic environment. This allowed adolescents to select the events they perceive to be most stressful and offered a more valid way to measure individual responses to real-life stressors.

The overarching goal of the current study was to examine whether and how physical activity influences depressive symptomatology from day-to-day, as well as

prospectively, in a community sample of urban adolescents. Potential mediators were also explored. Specifically, we expected coping self-efficacy and changes in biological stress systems (i.e., HPA axis) to be of particular importance in this relationship. We also explored whether any of these concurrent or prospective associations were moderated by gender.

Research Hypotheses

The following research hypotheses were tested:

1. At the within-person level, higher levels of (a) same day and (b) previous day physical activity will be associated with lower cortisol AUC.
2. At the within-person level, prior day cortisol AUC will not predict next day physical activity.
3. At the between-person level, youth who engage in more physical activity will exhibit lower cortisol AUC.
4. At the within-person level, higher levels of (a) same day and (b) previous day physical activity will be associated with lower levels of negative mood ratings.
5. At the within-person level, prior day negative mood will not predict next day physical activity.
6. At the between-person level, youth who engage in more physical activity will report fewer negative mood symptoms.
7. (a) Daily coping self-efficacy and (b) daily cortisol AUC will mediate the relationship between daily physical activity and with reduced same day negative mood rating at the within-person level.

8. Adolescents with higher levels of physical activity at T1 will have fewer self-reported symptoms of depression at T2, after controlling for depressive symptoms at T1.
9. T1 (a) coping self-efficacy and (b) cortisol AUC will mediate the relationship between physical activity at T1 and reduced depressive symptoms at T2, after controlling for depressive symptoms at T1.

In addition, the following research question was tested**:** Does gender moderate any of the above concurrent or prospective associations?

Method

Participants

Data for the current study were obtained from a larger longitudinal study on stress and coping among urban high school students (11-18 years old; 84% ethnic minority). Participants were recruited from three Chicago public school and completed an all-day data collection session at DePaul University (Time 1) and returned approximately 6-9 months later for a follow-up data collection session (Time 2). Data for the current study were drawn from a subsample of adolescents who were also invited to participate in a daily diary component of the study which required them to provide saliva samples and daily diary reports for 5 days. Participants were excluded if they were non-compliant with saliva sampling protocol (see procedure section for full compliance description).

Procedure

The study was approved by the Northwestern and DePaul University Ethics boards, and participants provided informed consent prior to participation. Consent and assent forms were collected for all participants. Each participant attended an all-day data

collection event at DePaul University on one of five consecutive Saturdays during the fall of 2012 (Wave 1). During the data collection day, participants completed various measures consisting of life stress interviews, depression questionnaires, health and executive functioning measures, and stress tasks. Research assistants demonstrated saliva sampling using the passive drool method. Participants in the current study consist of a subsample of adolescents who were invited to participate in a home-based data collection component of the study. Specifically, adolescents completed daily and nightly saliva samples and diary reports for five days. Morning diaries were used to record sleep and health behaviors. Evening diaries were used to report on daily stressors, physical activity, coping self-efficacy, and mood. Adolescents also reported on whether they consumed caffeinated drinks, cigarettes, alcohol, or medications on each evening daily diary. Adolescents returned for a follow-up session (Wave 2) during the spring of 2013. The same depression questionnaires were given at this data collection session; there was no daily diary portion at Wave 2.

Measures

***Depression Symptoms*.** Child reported depressive symptoms were assessed at Time 1 and Time 2 using the Children's Depression Inventory 2 (CDI 2; Kovacs, 2011). The CDI 2 is a self-report measure that assesses depressive symptoms in children and adolescents using 27 items rated on a 3-point scale from 0 - 2. Total scores range from 0 - 54 with higher scores indicating more depressive symptoms. The CDI has been shown to have good reliability and validity as a measure of depressive symptoms in youth (Klein, et al., 2005). Internal reliability in this sample was $\alpha = .90$ at Time 1 and $\alpha = .91$ at Time 2. Using the recommended clinical cutoffs revealed that 9% (CDI cutoff >19; Stark &

Laurent, 2001) or 15% (CDI cutoff >16; Timbremont et al., 2004) of youth were above cutoff scores for the CDI at time 1. At time 2, 10% (CDI cutoff > 19; Stark & Laurent, 2001) or 19% (CDI cutoff > 16; Timbremont et al., 2004) of youth were above cutoff scores.

Cortisol. Saliva samples were collected on each of the 5 diary days at wake-up, 30 minutes after waking, and at bedtime. Participants expelled saliva through a small straw into a 2 mL tube and labeled tubes with the time and date, as was demonstrated to them during the data collection day. Participants were instructed not to eat, drink, or brush their teeth 30 minutes before sampling. Samples were returned by mail and refrigerated at minus -80◦ C until they were shipped on dry ice to Trier, Germany, where they were assayed for cortisol. Intra-assay and inter-assay coefficients of variation below 5%. Based on prior research linking daily mood to diurnal cortisol (Adam et al., 2006) we measured the following indices of diurnal cortisol: (1) Cortisol Awakening Response (CAR) as measured by the increase in cortisol from waking to +30 min ; (2) diurnal slope from waking to bedtime; and (3) total cortisol output over 24 hours as indexed by area under the curve with respect to ground (AUCg) (Pruessner et al., 2003). Cortisol was log transformed prior to analyses to correct for positive skew in distribution.

Daily Negative Mood/Affect. Each night, participants rated how much they felt various negative emotions about their daily experiences using the following 5-point scale: 1= *"not at all*," 2= *"a little,"* 3= *"moderately,"* 4= *"a good amount,"* 5 = *"very much."* Ratings for "angry," "irritable," "sad," and "depressed" were used to measure daily patterns of negative affect in the current study. Daily negative affect was calculated by summing each participant's response for the negative emotions above. Aggregate

negative mood was created by averaging an individual's negative affect across the five diary days. We calculated the reliability of affect in accordance with Crandford et al.'s procedure (for formulas, see Cranford et al., 2006) which is based on generalizability theory (GT; Cronbach et al., 1972) and recognizes multiple sources of variance in diary measurements. Reliability estimates at the within-person level were above Rc= .72, which suggests that the four-item measure of negative mood in our 5-day diary study can assess within-person change reliably. Reliability estimates at the between-person level (i.e., individual differences in affect across study days), were above .94.

Daily Coping Self-Efficacy. On each evening diary, participants rated *"how capable did you feel about handling today's challenges?"* on the following five-point scale: 1= *"not at all,"* 2= *"a little,"* 3= *"somewhat,"* 4= *"a lot,"* and 5= *"extremely well"*, which represented daily coping self-efficacy. Mean coping self-efficacy was created by averaging an individual's coping self-efficacy ratings across the five diary days.

Daily Stress. On each evening diary, participants answered questions about their daily experiences and stressors. They rated how challenging their day was on the following five-point scale: 1= *"not at all,"* 2= *"a little,"* 3= *"somewhat,"* 4= *"a lot,"* and 5= *"extremely"* which represented daily stress. Mean stress was created by averaging participants' daily stress ratings across the five diary days.

Daily Physical Activity. Considering inconsistent findings between several of the studies reviewed earlier, we calculated both physical activity duration and intensity in order to identify which was most associated with mood outcomes. On each evening diary, participants rated how many minutes they spent engaging in light, moderate, and

vigorous physical activity using the following scale: *1= "none", 2= "less than 15", 3= "15-29", 4= "30-44", 5= "45-60", and 6= "more than 60."* Total PA for each day was calculated by summing each participant's response for light, moderate, and vigorous PA. Total moderate-vigorous PA for each day was calculated by summing each participant's response for moderate and vigorous PA only. Aggregate total PA variables were created by averaging an individual's total PA across the five sampling days. Aggregate moderate to vigorous PA variables were created by averaging an individual's moderate-vigorous PA across the five sampling days.

Data Analysis Plan

Preliminary Analyses

Demographics of the sample were calculated, and attrition analyses tested for group differences in those who completed measures at T1 and T2 compared to those who only completed T1. Data was analyzed for kurtosis, skewness, and extreme outliers. Descriptive statistics and correlations among study variables (physical activity, depressive symptoms, cortisol variables, daily stressors, daily mood, daily coping self-efficacy) and potential co-variates (age, gender, race, SES, pubertal status, BMI, sleep, as well as a dummy coded variable indicating use of medications and/or substances known to influence cortisol) were examined. Potential covariates were tested using independent samples *t* tests and analysis of variance; variables significantly related to at least one of the dependent variables or indicated by previous research were controlled for in primary analyses. Due to the large number of cortisol parameters (e.g., CAR, diurnal slope, AUC) examined in previous studies, we ran preliminary analyses to test which aspect of cortisol was most associated with physical activity (see Table 1 for results). Cortisol AUC was

the parameter identified as having the strongest association with physical activity was subsequently used in all primary analyses. Regarding prospective analyses, baseline (Time 1) levels of depressive symptoms were included as a priori covariates in analyses predicting Time 2 depressive symptoms.

Primary Analyses

Our daily diary data consisted of two levels, such that days (level 1) were nested within individuals (level 2). Therefore, we used multilevel modeling (Raudenbush & Bryk, 2002) with restricted maximum likelihood estimation to examine associations of daily PA levels with diurnal cortisol and mood patterns. MLM accounts for the nested structure of diary data and allows for estimation of both within-person (level 1) and between-person (level 2) effects. Moreover, MLM is the current gold standard for analyzing diary style data (see Nezlek 2011, 2012) because, unlike OLS, it can accommodate the variability among observations (Singer & Willett, 2009). We used a first-order autoregressive (AR1) structure for these models, which assumes homogeneous variances and correlations to be higher the closer together the observations are (Kwok et al., 2007).

To test within-person effects, time-varying (daily) scores were person-mean centered at level 1 by subtracting each individual's mean score across sampling days from their daily score. This allowed us to interpret level 1 effects in terms of an individual's deviation from their own mean. To test between-person effects, individuals' scores were averaged across days and grand-mean centered at level 2. This allowed us to interpret level 2 effects in terms of a person's deviation from the sample mean (Hoffman

& Stawski, 2009). Cross level interactions were used to test the moderating effects of gender (a level 2 variable) with daily cortisol AUC and negative mood (level 1 variables).

In order to better understand the direction of effects, we also ran cross lagged regression analyses within the MLM framework to test the timing of PA in relation to cortisol patterns and negative affect at the within-person level. This method allowed us to test for alternate direction of effects. Specifically, we examined whether prior day PA predicted diurnal cortisol patterns the next day, as well as whether diurnal cortisol patterns were associated with PA the following day.

All analyses were performed using SPSS 24 (IBM Corp, 2016); multilevel models were analyzed using the "MIXED" command and we reported unstandardized coefficients. Multilevel moderated mediation analyses were conducted using the MLmed SPSS macro (Hayes & Rockwood, 2020) which uses the Monte Carlo method to assess multilevel mediation. This allowed us to examine whether variations in potential mediators explained the effects of PA on negative mood. 95% confidence intervals using 10,000 bootstrap samples were constructed to test whether indirect effects were significantly different from zero. Prospective data were analyzed using the PROCESS macro for SPSS (Hayes, 2012).

Associations between physical activity and cortisol AUC

Hypotheses 1-3

Hypotheses 1-3 addressed the relationship between daily physical activity and cortisol AUC. At the within person level, AUC on day i for person *j* was modeled as a function of an intercept representing the person's average AUC (β_{0j}), a slope representing the change in AUC associated with daily PA (β_{1j}), and the within-person residual

representing the difference between the person's actual and predicted AUC that day (e_{ij}). At the between-person level, the level 1 intercept was a function of the sample average AUC (γ_{00}), the between-person association of PA with AUC (γ_{01}), and a random effect allowing the AUC intercept to vary across participants (u_{0j}). Predictors were person mean centered at level 1 (PA_{cw}) and grand mean centered (PA_{cb}) at level 2. Full models controlled for day at level 1 as well as covariates associated with AUC (pubertal status, SES, gender, stressors, and hours of sleep) at level 2. An example of a basic model with PA as the main independent variable is:

Level 1: $AUC_{ij} = \beta_{0j} + \beta_{1j}(PA_{cw}) + e_{ij}$

Level 2: $\beta_{0j} = \gamma_{00} + \gamma_{01}(PA_{cb}) + u_{0j}$

$\beta_{1j} = \gamma_{10} + u_{1j}$

Lagged Analyses: In the first equation, the lag from PA on day $n - 1$ to AUC on day n is estimated, and, in the second equation, the lag from AUC on day $n - 1$ to PA on day n is estimated. The lagged coefficients are, respectively, β_{2j}(pa day $n - 1$) in the first equation and β_{1j}(AUC day $n - 1$) in the second equation:

AUC(day n)$_{ij} = \beta_{0j} + \beta_{1j}$(AUC day n-1) + β_{2j}(PA day n-1) + r_{ij}

PA(day n)$_{ij} = \beta_{0j} + \beta_{1j}$(AUC day n-1) + β_{2j}(PA day n-1) + r_{ij}

Associations between physical activity and negative mood

Hypotheses 4-6

Hypotheses 4-6 addressed the relationship between daily physical activity and negative mood. Multilevel models were constructed similar to the cortisol models above. A description of the basic equation for PA and negative mood is described below:

Level 1: $\text{Negmood}_{ij} = \beta_{0j} + \beta_{1j}(\text{PA}_{cw}) + e_{ij}$

Level 2: $\beta_{0j} = \gamma_{00} + \gamma_{01}(\text{PA}_{cb}) + u_{0j}$

$\beta_{1j} = \gamma_{10} + u_{1j}$

Lagged Analyses: In the first equation, the lag from PA on day $n - 1$ to negative mood on day n is estimated, and, in the second equation, the lag from negative mood on day $n - 1$ to PA on day n is estimated. The lagged coefficients are, respectively, β_{2j}(pa day $n - 1$) in the first equation and β_{1j}(nmood day $n - 1$) in the second equation:

$\text{nmood(day } n)_{ij} = \beta_{0j} + \beta_{1j}(\text{nmood day } n\text{-}1) + \beta_{2j}(\text{pa day } n\text{-}1) + r_{ij}$

$\text{pa(day } n)_{ij} = \beta_{0j} + \beta_{1j}(\text{nmood day } n\text{-}1) + \beta_{2j}(\text{pa day } n\text{-}1) + r_{ij}$

Multilevel Mediation Analyses

Hypotheses 7a -7b

Hypotheses 7a and 7b tests lower-level (1-1-1) mediation effects (i.e., how and why changes in daily PA impact daily negative mood) using the MLmed SPSS macro (Hayes & Rockwood, 2020) which uses the Monte Carlo method to assess multilevel mediation. This allowed us to examine whether variations in daily coping self-efficacy or cortisol AUC explained the effect of daily PA on negative mood. 95% confidence intervals using 10,000 bootstrap samples were constructed to test whether the indirect effect through coping self-efficacy and cortisol AUC were significantly different from zero. These models tested random effects for the intercept and within-person predictors. Models and equations testing Cort AUC and Coping self-efficacy are presented in figures 1 and 2, respectively. Gender was tested as a conditional moderator of the *a* path.

Figure 1. Multilevel model depicting daily cort AUC as a mediator between daily PA and daily negative mood

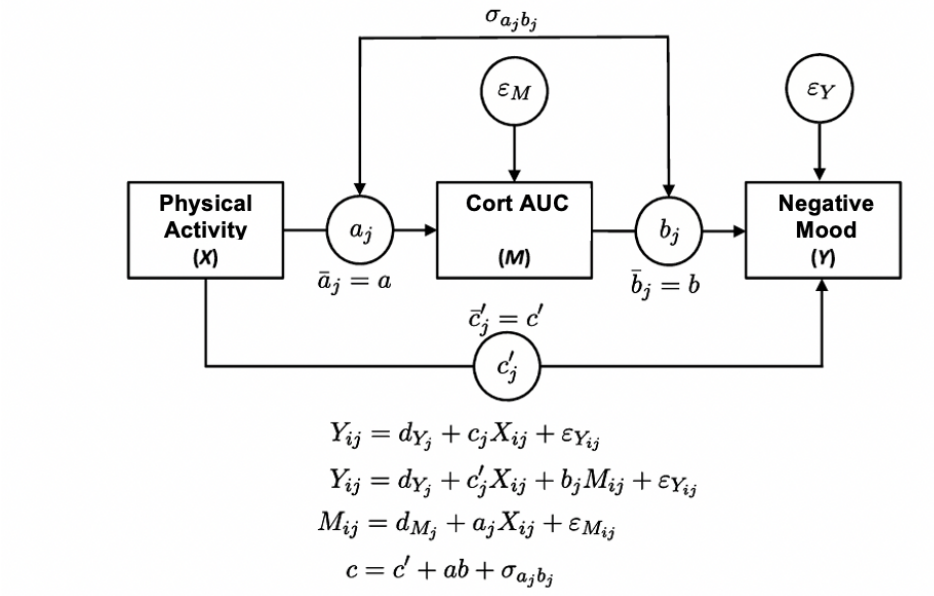
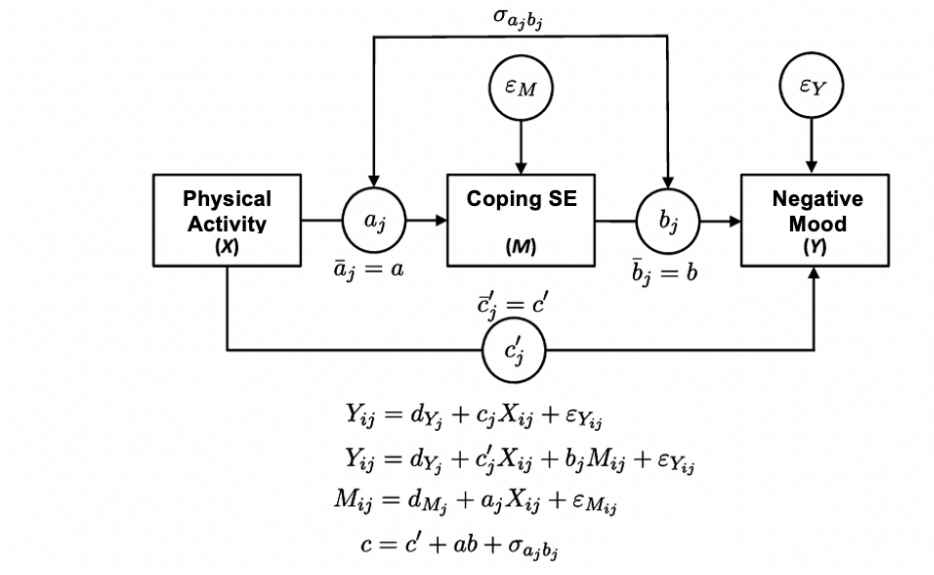


Figure 2. Multilevel model depicting daily coping self-efficacy as a mediator between daily PA and daily negative mood



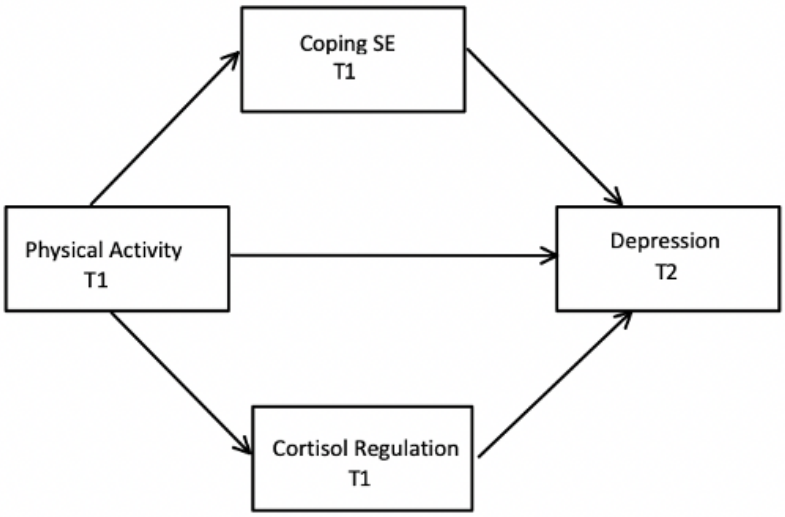
Prospective associations between PA and Depression

Hypotheses 8-9

To analyze hypothesis 8, hierarchical multiple regression was performed to examine the independent contribution of T1 PA in predicting CDI scores at T2 after controlling for T1 depression, age, and gender. Based on our exploratory research question, additional moderation analyses were conducted to test whether the impact of T1 PA on T2 depressive symptoms varied by gender. Regression models were run using PROCESS (Model 1; Hayes, 2017) to test the conditional effect of T1 PA on T2 Depressive Symptoms as a function of gender.

To analyze hypothesis 9, single-mediator path models were tested for each potential mediator– coping self-efficacy (9a) and diurnal cortisol AUC (9b) using the PROCESS macro for SPSS (Hayes, 2017) to test whether they mediated the relationship between physical activity at T1 and reduced depressive symptoms at T2, after controlling for depressive symptoms at T1. Next, we planned to enter any significant mediators identified in the single-mediator models into a multiple-mediator model in order to estimate their statistical significance and relative importance in accounting for the effects of PA on depressive symptoms. A conceptual example of one such model can be seen below in figure 3.

Figure 3. Coping self-efficacy and cortisol AUC as mediators between T1 PA and T2 depression



Results

Descriptive Statistics

Descriptive statistics and correlations for all study variables are displayed below in Table 1. Youth who dropped out of the study after time one did not differ from those who completed the study on the basis of gender, SES, race, physical activity, or depressive symptoms, although they were older in age, $t(105) = -3.64$, $p < .001$. Prior to conducting the main analyses, unconditional means models were examined to assess the means for daily level measures and estimated variance for each level of analyses. Means and variance components can be found in Table 2. AUC was used as the main cortisol outcome for subsequent analyses because it was the only cortisol parameter that was significantly associated with PA.

Table 1. Descriptive statistics and correlations for person-level averages of all study variables and covariates

	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	a. CAR	.																
2	a. AUC	.52***	.															
3	a. Diurnal slope	.24**	-.32**	.														
4	a. Neg Mood	.00	.09	-.01	.													
5	Sleep (hr per night)	-.26**	-.19*	-.07	-.15	.												
6	Depression Sx- T1	.17	.21**	.10	-.27**	.48***	.											
7	Depression Sx - T2	.09	.09	.13	-.31***	.43***	.66***	.										
8	PA - T2	.07	.13	.06	-.04	-.04	-.13	-.16*	.									
9	a. Total PA T1	-.06	-.14	.08	-.09	.01	-.18	.20	.29*	.								
10	a. Mod-Vig PA T1	-.13	-.19*	.12	-.02	.05	-.17	.29*	.19	.88***	.							
11	a. Coping SE	.03	.00	.04	-.31***	.05	-.44***	-.44***	.05	.05	.16*	.						
12	a. Stressors	.14	.06	-.12	-.16	.43***	.27**	.12	-.03	.12	.09	-.27**	.					
13	BMI (%ile)	-.07	-.03	.02	.03	-.12	.05	.18*	.19	.11	.08	-.14	.09	.				
14	Age	.17	.32***	-0.1	.41***	0.09	.20**	.15*	-.03	.00	-.07	-.05	.14	-.05	.			
15	Gender (male = 0)	.13	.24*	-.06	-.08	-.08	.20**	.17*	-.18*	-.09	-0.1	-.14	.09	.05	-.03	.		
16	Meds (no = 0)	-.11	-.23**	.07	.13	.07	.00	.01	.02	-.11	-.09	.00	.09	-.02	.07	.46	.	
17	SES	.01	-.13	.06	.18	.10	-.07	-.01	-.12	-.11	.00	.06	.01	-.31**	-.30***	.02	.17*	.
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	%	%	*M (SD)*
	Total sample	.12 (.21)	3.35 (1.85)	-.01 (.01)	6.51 (2.41)	7.32 (1.53)	9.08 (7.39)	8.64 (8.09)	12.90 (12.70)	7.84 (2.80)	4.40 (2.07)	3.24 (.97)	2.34 (.76)	70.41 (27.33)	14.75 (1.97)	100	.15 (.35)	42.95 (12.83)
	Females	.13 (.26)	3.83 (2.04)	-.01 (.01)	7.30 (2.58)	7.21 (1.74)	10.49 (8.12)	9.99 (9.28)	12.43 (10.05)	7.64 (2.95)	4.27 (2.08)	3.09 (.99)	2.46 (.80)	72.90 (24.53)	14.70 (1.97)	51.9	.14 (.34)	43.25 (13.27)
	Males	.08 (.15)	2.24 (.68)	-.01 (.01)	5.62 (1.99)	7.45 (1.22)	7.50 (6.01)	7.21 (6.56)	14.05 (11.07)	8.17 (2.67)	4.67 (2.11)	3.35 (.93)	2.24 (.68)	67.84 (29.76)	14.94 (1.92)	48.1	.17 (.38)	42.63 (12.64)

CAR = Cortisol awakening response; AUC = Area under the curve; T1 = Time 1; T2 = Time 2;
M = Mean; *SD* = standard deviation. *p < .05, ** p <.01, *** p <.001
a. Average score across 5 assessment days
X^2 is calculated for associations between two categorical variables

Table 2. Descriptive statistics for daily level measures

	Mean	**Variance Components**	
		Within-person	Between-person
Cortisol AUC	3.35	3.09	2.12
Cortisol CAR	0.12	0.04	0.02
Cortisol Slope	-1.30	0.12	0.03
PA	4.40	3.66	2.22
Negative Mood	6.51	5.53	3.93
Coping SE	3.24	0.83	0.58

Primary Analyses

Hypotheses 1-3

Separate multilevel models examined the relationship between daily cortisol AUC with concurrent and lagged daily PA. We did not find evidence to support hypotheses 1a or 1b as level 1 models did not show that same day or previous day PA was associated with cortisol AUC, see results in table below. Hypothesis 2 was confirmed as daily cortisol AUC did not predict daily PA. Hypothesis 3 was also confirmed, as there was a significant negative between-person association between PA and cortisol AUC (b = -.35, SE =.13, t = -2.78, p = .009), indicating that participants who reported more PA than other participants on average had lower average daily AUC across collection days compared to their counterparts. When level 2 covariates were added to the model, the between-person effects remained significant for cortisol AUC, suggesting the unique effects of PA on AUC above and beyond the effects of covariates. The coefficients for level 2 covariates showed that participants who were higher pubertal status, lower SES, and averaged fewer hours of sleep per night had higher AUC compared to their counterparts. Results from models testing associations between fluctuations in daily PA and cortisol AUC the same day are presented in Table 3.

Moderation Analyses

We did not find evidence of gender differences related to associations between PA and cortisol AUC.

Table 3. Two-level models of daily physical activity and AUC_g (nmol/L)

Fixed Effect	*B*	*SE*	*t*	*p*	CI
Intercept	3.56	1.31	2.72	0.01	[0.95, 6.17]
PA (WP)	0.33	0.19	1.80	0.09	[−0.57, 0.72]
PA (BP)	-0.35	0.13	-2.78	0.01	[−0.60, -0.09]
Sleep	-0.41	0.18	-2.16	0.04	[−0.79, -0.03]
Day	1.35	0.26	5.15	<.001	[0.82, 1.88]
Gender (1= Female)	-0.67	0.62	-1.08	0.29	[−1.92, 0.59]
Pubertal status	0.37	0.10	3.91	<.001	[0.18, 0.57]
SES	-0.40	0.02	-2.52	0.02	[−0.08, -0.01]

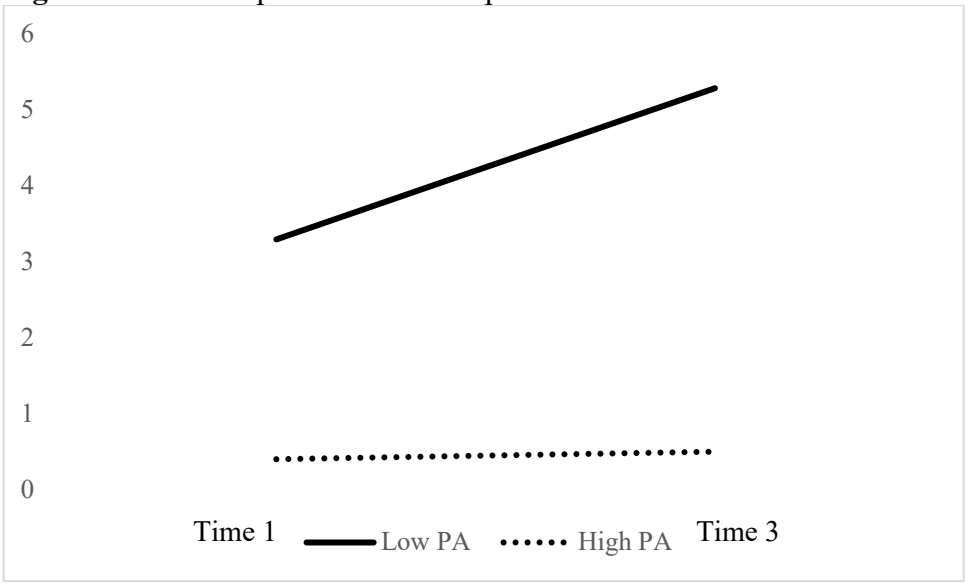
WP= within-person; BP= between-person

Table 4. Within-person fluctuations in previous day PA as predictor of AUC_g (nmol/L)

Fixed Effect	*B*	*SE*	*t*	*p*	CI
Intercept	3.77	1.82	2.01	0.04	[0.11, 7.42]
PA (WP)	0.43	0.23	1.84	0.07	[-0.04, 0.90]
PA (WP)_lag	-0.11	0.07	-1.58	0.12	[-0.24, 0.03]
Day	0.96	0.31	3.05	.004	[0.33, 1.58]
Gender	0.43	0.69	0.63	0.53	[-0.95, 1.82]

WP= within-person; BP= between-person

Figure 4. Between-person relationship between PA and cortisol AUC



Hypotheses 4-6

Separate multilevel models examined the relationship between daily negative mood with concurrent and lagged daily PA. At the within-person level, higher levels of same day (b = -1.63, SE = .56, p < .01) and previous day (b = -1.35, t = -2.21, p = .03) PA was associated with lower negative mood ratings, thus supporting hypotheses 4a and 4b.

Hypothesis 5 was also supported as prior day negative mood was not found to predict changes in next day PA. In support of hypothesis 6, there was also a significant between-person association between PA and self-reported negative mood symptoms, b = -0.24, SE = .12, p = .03, indicating that youth who, on average, had higher levels of PA also reported, on average, lower levels of negative mood symptoms. Results from models testing associations between fluctuations in daily PA and daily negative mood are presented in Table 4.

Supplemental Analyses

Given the significant findings above, we sought to extend the degree of temporal specificity, in line with recommendations by Wickham and Knee (2013) , by using a temporal analysis framework to explore whether responses to the predictor on the previous day magnified or attenuated associations between the predictor and outcome. The concurrent PA x lagged PA interaction was significant (b = -.05, t = -2.48, p < .05) and in the same direction as the first-order predictors, indicating a significant sensitization effect. That is, engaging in more PA than usual one day heightened the benefits of engaging in more than usual PA the next day when considering effects on negative mood.

Moderation Analyses

Results from lagged analyses revealed evidence of moderation effects by gender. Specifically, for girls, the coefficient representing the lag from PA to negative mood was negative and significant (b = -.31, t = -2.21, p = .03); whereas for boys, it was not significant (p > .05). Findings suggest that increases in prior day PA led to decreases in negative mood for girls, but not boys.

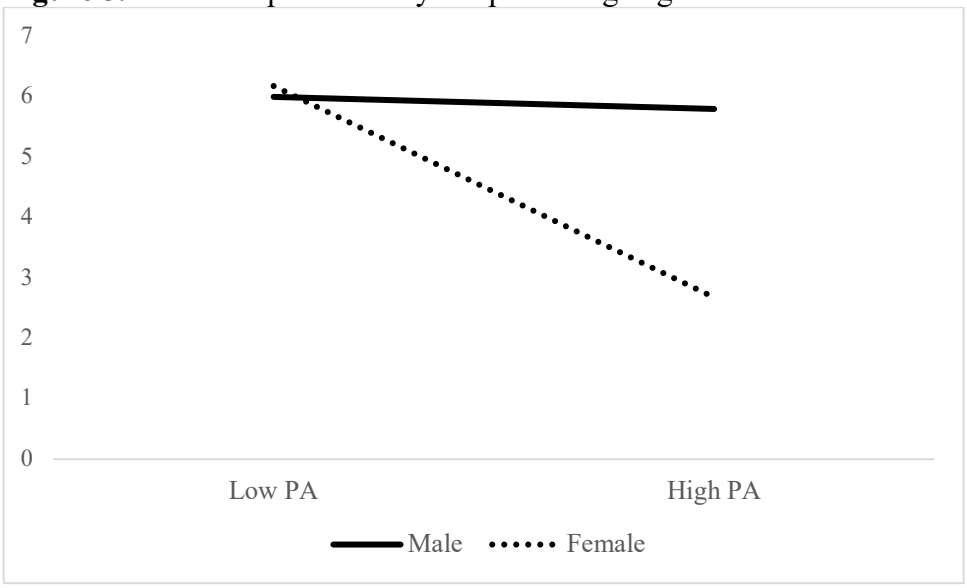
Table 5. Two-level model of daily PA and negative mood

Fixed Effect	*B*	*SE*	*t*	*p*	CI
Intercept	5.399	1.81	2.99	<0.01	[1.84, 8.95]
PA (WP)	-1.63	0.56	-0.91	<0.01	[−4.57, -0.72]
PA (BP)	-0.24	0.12	-2.00	0.03	[−0.48, -0.06]
Day	-0.18	0.14	-1.33	0.18	[-0.45, 0.09]
Gender (1= Female)	0.67	0.46	1.47	0.14	[−0.23, 1.56]
Age	-0.32	0.12	-.261	0.80	[-0.27, 0.21]

Table 6. Within-person fluctuations in previous day PA as predictor of negative mood

Fixed Effect	*B*	*SE*	*t*	*p*	CI
Intercept	6.50	0.27	24.22	< 0.001	[5.97, 7.03]
PA (WP)	-1.44	0.63	-2.29	0.02	[-2.68, -0.20]
PA (WP)_lag	-1.35	0.07	-2.21	0.03	[-0.44, 0.03]
Day	0.96	0.64	-2.11	.04	[0.33, 2.58]
Gender	0.43	0.69	0.63	0.53	[-0.95, 1.82]

Figure 5. Gender X previous day PA predicting negative mood



Hypotheses 7a-7b

The within-subjects indirect effect through coping SE was statistically significant, *(estimate* = -0.10, *SE* = 0.05, *z* = -1.96, *p* = 0.05, 95% CI [-0.21, -0.01], and the direct effect of PA became nonsignificant *(estimate* = -0.10, *SE* = 0,10 *t* = -1.00, *p* = 0.33, 95% CI [−0.31, 0.11]) when coping SE was include as a mediator the model. See Table 5 for full mediation path results. Our proposed mediation model was found to be statistically significant because the 95% confidence interval did not encompass zero

(95% CI = −0.21 to -0.01), thus confirming hypothesis 7a. Moreover, coping SE accounted for 49% of the variance for the PA effect on negative mood. When we tested whether gender (level 2) moderated the indirect effect of daily PA (level 1) on negative mood (level 1) through coping self-efficacy (level 1), we found evidence of multilevel conditional indirect effects at 95% CI as evidence from the index of moderated mediation (*estimate* = 0.19, CI [.05, 0.35]) reported in Table 5.

In contrast, we did not find support for hypothesis 7b; the within-subjects mediation effect of cortisol AUC was not significant *(estimate* = -0.09, *SE* = 0.06, *z* = -1.39, *p* = 0.16, 95% CI [−0.21, 0.03)], and the direct effect of PA on negative mood remained significant when cortisol AUC was included in the model *(estimate* = -0.24, *SE* = 0.11, *t* = -2.25, *p* = 0.03, 95% CI [−0.46, -0.02]). Results suggest that coping SE might be a mechanism through which PA influences negative mood symptoms for girls.

Table 7. Multilevel moderated mediation analyses

	B	**SE**	***t***	**95% CI (LL,UL)**
Daily PA (X) → Daily Negative Mood (Y)	-0.20	0.11	-1.82	[−0.46, -0.02]
Daily PA (X) → Daily Negative Mood (Y)	-0.10	0.10	-1.00	[-0.31, 0.11]
Daily PA (X) → Daily Coping SE (M1)	0.26	0.14	1.86	[0.20, 0.53]
Daily PA (X) → Daily Cortisol AUC (M2)	0.28	0.15	1.87	[-0.02, 0.59]
Daily Coping SE (M1) → Daily Negative Mood (Y)	-0.99	0.18	-5.50	[-1.28, -.33]
Daily Cortisol AUC (M2) → Daily Negative Mood (Y)	0.22	0.18	1.22	[-0.12, 0.57]
Daily Coping SE (M1)	-0.10	0.05	-1.96	[−0.21, -0.01]
Daily Cortisol AUC (M2)	-0.09	0.06	-1.39	[−0.21, 0.03]
Index of moderated mediation	**0.19**			**[0.05, 0.35]**

Hypotheses 8-9

For hypothesis 8, hierarchical multiple regression was performed to examine the independent contribution of T1 PA after controlling for T1 depression, age, and gender.

Regression statistics are reported in Table 6. The first model predicted T2 depression scores, hypothesis 8a. T1 PA was entered in the second step of the analysis after entering age and T1 depressive symptoms in the first. In step one, T1 depressive symptoms made the only significant contribution to the regression model (b = .76, p < .001). Age and T1 depressive symptoms accounted for 37.3% of the variation in T2 depressive symptoms. In step two, T1 PA made a significant contribution to the model (b = 1.44, p =.003) when controlling for age and T1 depressive symptoms and accounted for an additional 10.4% of the variation in T2 depressive symptoms. The overall model was significant, F (3, 49) = 14.92, p < .001.

Table 8. T1 physical activity predicting depressive symptoms at follow-up

	B	*SE*	*t*	*p*	R^2	ΔR^2
Step 1					0.39	0.39***
T1 CDI	0.82***	0.16	5.21	<.001		
Age	0.33	0.55	0.60	0.55		
Gender	-2.07	2.17	0.95	0.35		
Step 2					0.49	0.10***
T1 PA	1.43**	0.46	3.10	<.01		

*p < .05, **p < .01, ***p < .001.

Moderation Analyses

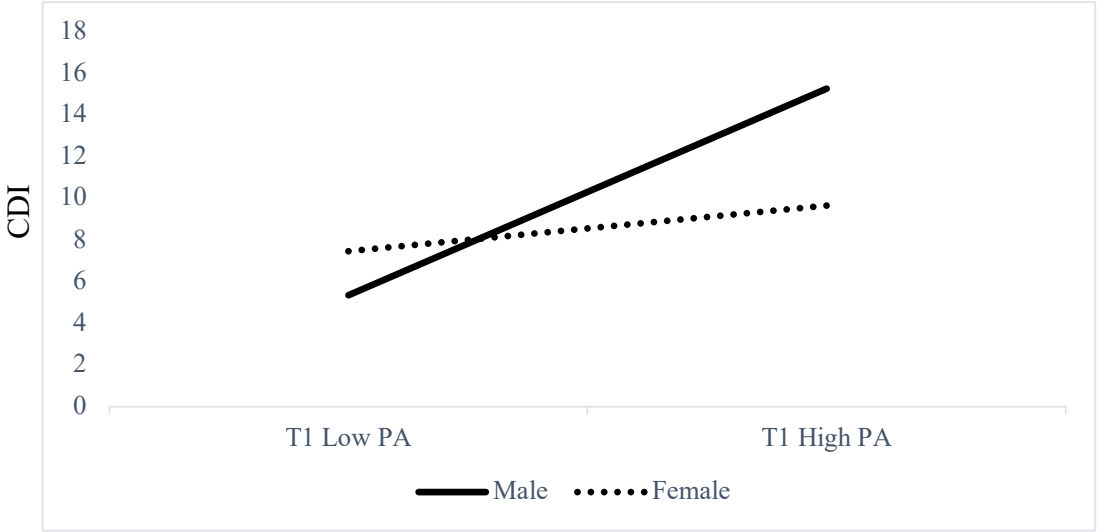
Based on our exploratory research question, additional moderation analyses were conducted to test whether the impact of T1 PA on T2 depressive symptoms varied by gender. Regression models were run using PROCESS (Model 1; Hayes, 2017) to test the conditional effect of T1 PA on T2 Depressive Symptoms as a function of gender. We regressed T2 Depressive Symptoms (Y) on T1 PA (X), Gender (W), and the product of T1 PA and Gender (XW). As in previous analyses, T1 depressive symptoms and age

were included as covariates. There was a significant interaction between T1 PA and gender in predicting depressive symptoms at T2, controlling for T1 depressive symptoms (b = -1.89, p =.04, R2 change = .05). Both T1 depression symptoms (b = .82, p < .001) and T1 PA (b = 2.43, p < .001) were significant predictors in this model. The overall model was significant [F (5, 47) = 10.74 p <.001] and explained 53% of the variation in T2 depressive symptoms. Regression statistics are reported in Table 7. Simple slopes analysis was conducted to probe the nature of this interaction and test the conditional effects of T1 PA by gender. For males, there was a significant positive relationship between T1 PA and T2 Depressive symptoms (b = 2.439, 95% CI [1.13, 3.72], t = 3.77, p < .001); whereas for females, the relationship was nonsignificant (b =.53, p = .39).

Table 9. Interaction between T1 PA and gender in predicting depressive symptoms at T2

	B	***SE***	***t***	***p***
Constant	2.54	6.92	0.37	0.01
T1 PA	2.43	0.64	3.77	<.001
Gender	-1.75	1.93	-0.90	0.37
T1 PA X Gender	-1.89	0.88	-2.14	0.04
T1 CDI	0.82	0.14	5.84	<.001
Age	0.07	0.50	0.14	0.89

Figure 6. Gender differences in the association between T1 PA and depressive symptoms at T2



Mediation analyses were not supported (hypothesis 9); that is, neither coping self-efficacy nor cortisol patterns accounted for the effects of PA on depressive symptoms over time.

Discussion

The current study investigated daily and prospective associations of physical activity with depressive symptoms in adolescence. Using an intensive daily diary study, we examined within- and between-person associations of daily physical activity with cortisol and negative mood, and associated mechanisms of influence. We found that youth who engaged in more daily physical activity tended to have lower cortisol AUC and report fewer negative mood symptoms. At the within-person level, same day and previous day physical activity was negatively associated with negative mood. Coping self-efficacy played an important role in explaining the relationship between PA and negative mood for girls, but not boys. There was limited evidence for longer-term prospective associations in the current sample. Findings highlight the importance of differentiating within- and between-person associations and provide initial evidence that day-today variability in PA can influence stress systems and lead to changes in mood among urban adolescence.

Associations Between Physical Activity and Cortisol AUC

Consistent with our hypothesis, we found evidence of between-person associations (variables averaged across the 5 days of assessment), showing that greater average daily PA was related to lower average daily cortisol AUC. This finding – that youth who are more active have lower levels of cortisol output throughout the day – is consistent with several lines of research showing how regular physical activity over time

leads to decreased cortisol levels (McHale et al., 2012; Urizar et al., 2010). This relationship is also consistent with Salamon's stress adaptation model (Sothman et al., 1996) as it demonstrates how intentionally and repeatedly engaging in a physical stressor can cause long-term adaptations to stress response systems. Moreover, this finding supports the notion that biological stress response systems play an important role in the PA- depression link, and is consistent with findings from PA interventions in adult samples, such as (Nabkasorn et al., 2006)who found a reduction in depressive symptoms in parallel with a reduction in 24-hour cortisol secretion among depressed women after 8 weeks of increased PA. Although several PA interventions have been shown to reduce symptoms of depression in adolescents (Carter et al., 2016; Bailey et. al., 2017), none have also examined how these PA interventions affect cortisol parameters. Going forward, it will be important to not only study whether PA interventions work for adolescents with depression, but also how any why they work.

At the within-person level, we hypothesized that higher levels of daily PA would be associated with lower cortisol AUC. Although within-person associations did not rise to the level of significance in our sample, they were in the expected direction (i.e., on days that youth engaged in more PA than they usually do, they tended to have higher cortisol AUC than they usually do that same day). The fact that we found associations between PA and cortisol between people, but not within individuals suggests that effects of PA on cortisol may take more time to develop than we were able to capture in our five days of sampling. More intensive longitudinal designs – studies with longer study periods and more time points – are needed to investigate the relationship between PA and cortisol trajectories over time. It is possible that these effects accumulate over time, perhaps

taking months or years to show a measurable impact. This notion is supported by prior studies in adults showing how persistent daily alterations in cortisol patterns can lead to stable changes that influence functioning (for review, see McEwen, 2007) Thus, additional research is needed to examine how these patterns unfold over time in adolescents.

It is also possible that other biological stress pathways, such as the autonomic nervous system (ANS) may show stronger associations with PA. For example, Skoluda et al. (2015) investigated biological and psychological responses to several common laboratory stressors (Stroop test, cold pressor test, Trier Social Stress test, and a bicycle ergometer test) in a small sample of healthy young adult men. They found the highest HPA axis response was associated with the psychological stressor (TSST) while the highest ANS response occurred in response to the physical stressor (Ergometer), suggesting physical stressors such as PA may more directly activate the ANS while psychological stressors may more directly activate the HPA axis. Extant research also indicates the ANS is a faster responding system compared to the HPA axis, which could make it easier to model fluctuations at the daily level. Thus, studies examining associations between daily PA and markers of the ANS, such as salivary alpha amylase (sAA) may represent an important next step to understanding biological mechanisms related to PA's effects on mood.

Associations Between Physical Activity and Negative Mood

Consistent with our hypotheses, we found evidence for associations between PA and affect regulation at the within- and between-person levels, suggesting it may represent another pathway through which PA reduces depression. Within individuals, on

days when youth engaged in higher levels of PA compared to their daily average, they reported significantly fewer negative mood symptoms that evening. Between individuals, youth who, on average, had higher levels of PA also reported, on average, lower levels of negative mood. It is important to note that our negative mood/affect variable measured individuals' self-reported negative affect in response to that day's stressors, thus measuring negative affect reactivity. Such findings are in line with previous studies such as Puterman and colleagues (2017) who found that adults who regularly engaged in daily PA showed reduced negative affect response to daily stressful events. These findings also add to the growing evidence of acute and cumulative benefits of PA on coping with stress (Edwards, 2006; Puterman et al., 2011b). Our study is one of the first to demonstrate acute and cumulative effects in the same study as well as in an adolescent sample. This represents an important extension of the current literature as accumulated effects of high emotional reactivity to stress is known to increase risk for adolescent depression (Booij et al., 2018). Moreover, we were able to demonstrate how these within- and between-person associations manifest in adolescents' daily lives and in response to naturalistic everyday stressors, which strengthens confidence in the generalizability of these findings.

By integrating estimates of concurrent and lagged effects, we were also able to shed light on the direction of association between PA and negative mood. Overall, we found stronger support for more PA predicting less negative mood compared to the opposite direction of effects. We also found preliminary evidence for cumulative effects. Specifically, our temporal analyses found evidence of sensitization effects for girls, such that higher levels of PA on the previous day exacerbated the concurrent effects of PA the next day. Temporal analysis is a relatively new modeling technique and has not been

used to examine associations between daily PA and mood, so we cannot compare our finding with previous research. Nonetheless, this statistical framework represents an exciting opportunity to investigate how everyday occurrences can have an impact both in the moment and prospectively over time. For example, our sensitization finding suggests the frequency of PA may be more important than the total quantity (i.e., engaging in daily PA may be more beneficial than hitting a weekly number of total minutes). Knowing that girls are more responsive to PA when they also engaged in PA the previous day could have important implications for physical education (PE) guidelines. For instance, schools may wish to make PE a daily class instead of scheduling it on alternating days. Because our study was limited by only having five consecutive days of data collection for the diary portions, it will be important to replicate the results of our temporal analyses in studies with longer sampling periods.

Multilevel Mediation Through Coping Self-Efficacy

Extending on our finding that daily PA influenced daily mood, we ran lower-level multilevel mediation analyses to better understand how daily PA affected daily negative mood. As hypothesized, coping self-efficacy emerged as a significant mediator in this relationship. This finding is consistent with prior knowledge that adolescents who exercise more regularly tend to report higher perceived ability to cope with stress (Kishida, 2015; Mata et al., 2013) and that higher levels of coping self-efficacy are generally associated with reduced symptoms of depression (Shields et al., 2010). Unlike previous studies, which have mostly viewed coping self-efficacy as a stable trait, we found evidence of dynamic relationships between PA, coping self-efficacy, and negative mood within individuals at the daily level. Results not only provide insight into the causal

direction of associations but demonstrate how even small increases in daily PA can produce alterations in an individual's coping self-efficacy and negative mood within the same day. This is particularly exciting considering that PA is a modifiable behavior and could easily be targeted with intervention strategies.

That an individual's coping self-efficacy for daily stressors at least partially accounted for the effects of daily PA on daily negative mood further supports the idea of cross-stressor adaptation (Sothman et al., 1996). That is, we showed how purposely engaging in a physical stressor (PA) led to changes in the way some individuals perceived their ability to respond to psychological stressors. Moreover, this finding supports Bandura's idea that self-efficacy from one domain can influence self-efficacy in another domain, another concept that warrants further exploration with regard to PA. Given that coping self-efficacy emerged as a mechanism of particular interest, additional research should explore which aspects of coping self-efficacy are most salient in reducing depressive symptoms. We were unable to do this in our study because we used a single question (i.e. "how confident did you feel in your ability to handle today's stressors?") as a proxy for coping self-efficacy. Thus, future studies should examine associations using standardized measures that contain separate constructs of coping self-efficacy to see how day-to-day variations in these constructs are related to changes in PA and mood. It will also be important to understand whether coping self-efficacy is more associated with certain types of PA or under certain contexts.

Surprisingly, the indirect effect of coping self-efficacy was not significant for boys, which suggests there may be other processes or mechanisms accounting for the effect of PA on negative mood for boys. Another possibility is that our null findings

regarding mediation for boys could be due to floor effects – that is, those that reported lower levels of negative mood (boys) did not have much lower to go in terms of effects of PA. While we found no evidence in support of cortisol AUC as a mediator, additional studies are also needed to examine other cortisol parameters as potential biological mediators, such as CAR and diurnal slope. For example, Drogos and colleagues (2019) found that an aerobic PA intervention was associated with significant shifts in CAR, but not AUC, in a community sample of adults, and that these shifts in CAR were associated with greater reductions in perceived stress. Overall, further research is needed to explore additional biological mediators as well as mechanisms that might explain the beneficial effects of PA on negative mood for boys.

Prospective Associations Between Physical Activity and Depressive Symptoms

Results from prospective analyses were somewhat counter to our hypotheses. Time 1 PA was not a significant predictor of depressive symptoms at time 2 for girls, whereas for boys, the relationship was significant but in the opposite direction than predicted. This is inconsistent with findings from other studies such as McPhie and Rawana (2012) which showed higher levels of PA in early adolescence were associated with lower levels of depression, and slower increases in depression symptoms through emerging adulthood. However, McPhie & Rawnana's study also found evidence of gender and age differences in their sample, such that PA and depressive symptoms were not significantly associated for early adolescent girls whereas they were for late adolescent girls as well as early and late adolescent boys. Results also conflict with findings from the adult literature showing that low levels of PA are more significantly associated with prospective increased risk for depression in women compared to men (Mikkelsen et al., 2010). Based on these findings,

future research should continue to explore gender and age differences to improve our understanding of how these associations evolve over the adolescent transition.

Strengths and Limitations

This study extends previous findings of associations between physical activity and depression by showing the mediated relationship among daily PA, coping self-efficacy, and negative mood at the daily level. Our ability to account for significant day to day variability represents a strength of the current study and one that studies with between-subjects designs have not been able to capture. Another strength is our measurement of biological and psychological stress pathways within the same study. Previous investigations have tended to study these pathways in isolation, which has made it difficult to compare effects and identify interactions. Finally, our use of daily diaries and saliva sampling allowed us to measure daily dynamics of stress processes and PA outside of a laboratory setting and within the context of adolescents' everyday lives, thus increasing ecological validity.

Several limitations should be considered while interpreting results from the current study. First, the majority of our data came from youth self-reported symptoms (i.e., negative mood, depression, daily stressors, coping self-efficacy, physical activity) which could be prone to recall bias. There is existing evidence of adolescents overestimating activity levels when using subjective reports compared to objective measures (Prince et al., 2008). On the other hand, end of day daily diary methods (such as the one we used) are associated with improved recall bias compared to study designs with longer recall periods (Stone & Shiffman, 2002). Second, our study did not control for the time of day that PA occurred. It is possible that the effects of PA on mood may be stronger at

different points in the day—for example, morning vs evening. Thus, our measurement of PA may not have been sensitive enough to detect short-term fluctuations, which may explain some of our null findings. Future studies should incorporate objective measures of PA, such as accelerometers, which would allow researchers to not only quantify physical activity levels with more precision, and more accurately assess the timing of effects, but would also help clarify dose-response relationships between PA and mood. An important next step will be to replicate findings using objective measures of PA. Clarifying the frequency, duration, and intensity of PA associated with optimal outcomes in adolescence will help design more targeted interventions and inform policy related to PA guidelines for youth.

A second limitation related to physical activity measurement is that we did not measure PA in a way that allowed us to examine differences by modality. Youth reported the amount of time they spent engaging in low, moderate, and vigorous PA. This allowed us to examine differences in subjective duration and intensity, but it did not tell us the specific forms of PA participants were engaging in. This is an important limitation as there is evidence that aerobic activity is associated with higher increases in cortisol secretion compared to resistance training (for review, see Torres et al., 2021). Other unmeasured aspects of PA could have also confounded results. For example, PA that incorporates social interaction, such as team sports or group exercise classes, could have different effects on negative mood than PA done by oneself. For example, a recent study in a large community sample of adults found that participating in a sport or exercise group protected against depression by reducing loneliness, in addition to increasing levels of physical activity (Stevens et al., 2021). Therefore, additional studies are needed to

investigate potential contextual effects and replicate findings with regard to sports participation and social PA.

Another limitation of the current study is that we only focused on negative mood symptoms. Considering that depression is classified by symptoms related to both negative and positive affect, future studies should investigate both dimensions of affect in parallel in order to facilitate a more comprehensive understanding of the relationship between PA and depression. For example, there is initial evidence within the adult literature that self-reported episodes of physical activity may be associated with increased positive affect in (Fortier et al., 2015); however, this research still needs to be replicated in adolescents.

Implications

Findings from the current study have several implications for policy, practice, and future research. In terms of policy implications, our results emphasize the importance of regular PA over adolescence and highlight the need for policymakers to increase opportunities for youth to engage in daily PA. One way to do this is through physical education (PE) guidelines in schools. Schools not only represent the setting where adolescents spend most of their time, but also where they have the most opportunity to engage in PA. According to the Youth Risk Behavior Surveillance System – a national survey conducted by the Centers for Disease Control (CDC), only 20% of high school students were meeting the recommended amount of aerobic and muscle-strengthening activity in 2017 and that number dropped to 16.5% in the latest 2019 report. At the same time, school-based opportunities for PA are decreasing due to various reasons (e.g., budget cuts, more focus on academics, and lack of resources). In fact, only two states currently require high school students to meet the national recommendation of (225

minutes per week) of time in PE (Piekarz-Porter et al., 2021). As such, state lawmakers should utilize the results of this study to allocate funds and adopt stronger laws that require schools to meet national PE guidelines and promote daily PA for adolescents.

Clinically, PA appears to be a promising target for adolescent depression. While additional research is needed to understand these associations in clinical samples of youth, our findings suggest that depression interventions which incorporate an active component may be particularly effective for adolescents. Moreover, our results suggest that providers working with adolescents – especially those endorsing high levels of stress – should consider assessing PA levels more thoroughly. This could be accomplished through methods such as wearable devices (Yang et al., 2018) , daily surveys, or phone apps (Murphy et al., 2020). PA is rarely assessed in adolescents seeking treatment for depression (Iverson 2004) and thus represents an accessible and affordable treatment option that is currently underutilized. PA may also represent a treatment option associated with less negative stigma than traditional treatments for depression, which could be appealing for some groups of adolescents. Further, we found evidence for benefits of PA at the daily level, suggesting PA may offer more immediate benefits compared to other treatments modalities (i.e., psychotherapy, pharmacological) that can sometimes take weeks to impact symptoms. In fact, several adult PA interventions have now shown significant treatment effects comparable to psychotherapy and psychopharmacology interventions (Blumenthal et al., 2007; Dinas et al., 2011; Kvam et al., 2016); further replication is needed among adolescents.

At the theoretical level, our findings extend on previously known inverse associations between PA and depression by shedding light on causal pathways through

which PA may help reduce depression symptoms among adolescents. Elucidating such pathways is critical in developing more targeted treatments for this population. Utilizing more sophisticated modeling techniques such as muti-level moderated mediation allowed us to identify how PA may operate via different mechanisms for different groups of individuals. For example, we found that daily PA reduced daily negative mood for girls by increasing their coping self-efficacy. Knowing how and why girls particularly benefit from daily PA has important clinical implications as previous research shows an increase in rates of depression and a decrease in rates of PA over adolescence – these trends were also found in the current study. Moreover, we demonstrated the utility in designing studies that allow researchers to examine not only how people differ from one another, but also how and under what circumstances they differ from themselves. Future studies are needed to continue this line of research and the current study provides a blueprint for how to examine such research questions.

Conclusion

Overall, this study examined concurrent and prospective associations between physical activity and depressive symptoms in adolescence and two theoretically informed mechanisms of influence, the HPA axis and coping self-efficacy. Findings suggest that regular physical activity can reduce daily cortisol– a stress hormone that is often elevated in individuals with depression. Findings also suggest that after youth engage in more PA than is typical for them, they experience fewer negative mood symptoms; and that for girls, this is in part because they experienced greater confidence in their ability to handle daily stressors. Given known increases in rates of depression over the adolescent transition, especially for girls, findings underscore the importance of further investigation

into the within- and between-person associations of physical activity with mood. Understanding how these associations unfold will be especially important for informing prevention and intervention efforts for vulnerable adolescents who may not be meeting the recommended physical activity guidelines.

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Appendix A. Measures

Health Questionnaire

Health Information
ID#_____

Certain lifestyle choices, medications and health states affect people's levels of cortisol, the stress hormone that we are measuring in your saliva. We need to know about these so we can take them into account when analyzing your stress hormone levels. We realize that many of the questions below will not be relevant to you, but we need to ask them of everybody. Please answer the following, remembering that you may skip any question you do not wish to answer, and that all of your answers are confidential. **Thank you!**

1. Do you regularly take any form of caffeine? (coffee, tea, caffeinated pop, caffeine pills, etc.) Yes No

   - If yes, please indicate what form you take it in and how much you take each day.

   Form _____ Quantity _____ (amount/day).

2. Do you smoke or take nicotine in any other form? Yes No

   - If yes, please indicate what form you take it in and how much you take each day.

   Form _____ Quantity _____ (amount/day)

3. Do you ever consume alcoholic beverages? Yes No

   - If yes, how many drinks containing alcohol (wine, beer, etc.) do you consume per week? _____ drinks.

Males, please skip to Question 6. ->

4. ***(Females only)*** Do you have a monthly menstrual cycle? Yes No
   - If yes, how many days has it been since the beginning of your last menstrual period? _____ days
   - If no, please indicate the reason:

     ☐ Currently Pregnant ____ months
     ☐ Haven't had a period yet
     ☐ Other (please describe): _____

   Do you currently use birth control pills or a birth control implant or injection? Yes No
   If yes, please indicate type: _____

5. Are you currently diagnosed with asthma? Yes
   No
   - If yes, do you currently take any form of asthma medication? Yes
     No
   - If yes, what type(s)? _____

6. Do you have any allergies? Yes
   No

- If yes, please list _____

- If yes, are you taking any medications to control these allergies? Yes No

- If yes, please list _____

7. Are you currently taking medication for depression or another mental illness? Yes No
   If yes, please list the medication(s) _____

8. Do you ever take any other medications, beyond those already described above? If yes, please list the medications, how often you take them and for what reasons.

   _____

9. Do you have any other health conditions we should be aware of? If yes, please list.

   _____

10. Do you currently perform any form of regular physical exercise? Yes No
    - If yes, please indicate what types of exercise you do how often you do each.

    _____

11. Please list any other things you do for the purpose of promoting your physical and/or emotional health.

    _____

12. In times of ill health or upset, how easily can you find someone to help you with your:

	Not at all				Extremely Easily
Physical needs?	1	2	3	4	5
Emotional needs?	1	2	3	4	5

	Often	Hardly Ever	Some of the Time
13. How often do you feel that you lack companionship?	1	2	3
How often do you feel left out?	1	2	3
How often do you feel isolated from others?	1	2	3

14. On average, how many hours of sleep do you get per night? _____ (hours)

    I typically go to bed between the hours of _____ and _____

    I typically get up between the hours of _____ and _____

    How long (in minutes) has it usually taken you to fall asleep each night? Number of minutes _____

    About how many days per week do you wake feeling rested? 1 2 3 4 5 6 7

15. During the past month, how often have you had trouble sleeping because you cannot get to sleep within thirty minutes? **Not at all** **One time a week** **Two times** **Three + times**

❑ ❑ ❑ ❑

16. During the past month, how often have you had trouble sleeping because you wake up in the middle of the night or the early morning? **Not at all** **One time a week** **Two times** **Three + times**

❑ ❑ ❑ ❑

17. During the past month, how often have you had trouble staying awake while eating meals, engaging in social activities or sitting in class?

Not at all **One time a week** **Two times** **Three + times**

❑ ❑ ❑ ❑

18. During the <u>past month</u>, how would you rate your sleep quality overall?

Very Good **Fairly Good** **Fairly Bad** **Very Bad**

❑ ❑ ❑ ❑

19. One hears about "morning" and "evening" types of people. Which ONE of these types do you consider yourself to be?

Definitely a "morning" type _____
Rather more a "morning" than an "evening" type_____
Rather more an "evening" than a "morning" type_____
Definitely an "evening" type _____

20. How tall are you? _____ ft _____ in

How much do you currently weigh? _____lbs

How much did you weigh a year (12 months) ago? _____ lbs

What is your ideal or desired weight? _____ lbs

How much did you weigh at birth? _____lbs_____ oz

If you don't know your exact birthweight, please circle your closest guess as to your birthweight:

<5 lbs 6 lbs 7lbs 8lbs 9lbs >10 lbs Really don't know

To the best of your knowledge, were you born early, on time, or later than your expected due date?

Early (by ____ weeks) On Time Late (by ____ weeks) Really don't know

21. Basically, would you say your health is (circle one):

Excellent Above Average Average Below Average Poor

22. Do you have any additional comments about your health or lifestyle?

Comments?
_____
_____
_____
_____

Thank you!

Daily Diary Instructions

Cities Daily Diary Study Instructions

Thank you for participating in the Cities Daily Diary Study! This booklet contains instructions for how to complete this part of the study, including how to:

- Take saliva samples
- Use the sleep watch
- Fill out morning and evening diaries
- Complete your iPod cognitive tasks
- Store your samples

- Return your materials

The Daily Diary Study will start on the Saturday evening of your visit to DePaul University. You will complete the study tasks until Wednesday morning, and return the materials to us at your school on Thursday. See below for the activities you will complete each day.

	Saturday (Day 0)	Sunday (Day 1)	Monday (Day 2)	Tuesday (Day 3)	Wednesday (Day 4)	Thursday
Sleep Watch	√	√	√	√	√	Bring your diaries, sleep watch, sample, and iPod with you to school!
Morning Saliva		√	√	√	√	
Morning Diary		√	√	√	√	
Cognitive Tasks		√	√	√	√	
Evening Saliva	√	√	√	√	*	
Evening Diary		√	√	√	*	

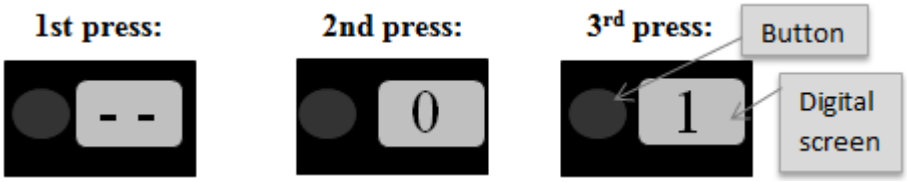
*If you forget to perform any of the tasks that are part of your daily diary during Saturday through Wednesday morning, you can use Wednesday evening through Thursday morning to make up for some of the missed tasks. It is very important that you do these daily diary procedures as instructed each day.

We will link the stressful events you reported on your questionnaires, interviews, and your diaries to biological signs of stress (stress hormones) in your saliva, and to your sleep quality. We hope to identify what types of events are most stressful for people your age, and also how to reduce the negative impact of stress.
We will review and practice all of the procedures below with you in person during your first DePaul visit, The instructions below are for your reference in case you forget. If you have any questions, please feel free to call your Diary Study Helper _____ at _____ or e-mail him/her at citiesdailydiarystudy@gmail.com

Day-by-Day Instructions

This will be done during the week after your visit to DePaul

Saturday Night: Your sleep watch should have been put on your wrist during your visit to DePaul. If you haven't yet put on your sleep watch, attach the watch on the wrist of your non-dominant (the hand that you do not write with). Keep the watch on your wrist, all day and all night, until Wednesday morning. Each night, starting Saturday night, when you are in bed and ready to go to sleep, you should push the button on the watch 3 times, until you see a "1" appear. You should also push the button 3 times in the morning when you wake up, to let the watch know that you are now awake!



If you forget to press the button, don't worry, but try to remember next time!

You can wear the watch when you are showering or doing dishes, but please remove it if you take a bath or if you are going swimming or diving. You can re-attach the watch using he extra wristband we provided. On Wednesday morning, you can cut the watch off and place it carefully in the box that the watch came in, inside the carry pouch we provided. Please be careful not to damage or lose the watch – it is very expensive!

Immediately before going to bed on Saturday night (but before you brush your teeth), you should take your first saliva sample, as instructed earlier in the day. You should also place your saliva sampling kit beside your bed tonight, and put it there each night so that it is available as soon as you wake up!

Sunday Morning: This morning, as soon as you wake up, you will press the button on the sleep watch and take your first saliva sample. You will take your second morning sample 30 minutes later. Please follow the detailed instructions for taking samples on the next page. You will also complete a morning diary entry and cognitive tasks on the iPod this morning. Your iPod should always remain stored in the zippered pouch when it is not being used for the study, and must be returned with your other materials on Thursday.

Sunday Evening: You will do another saliva sample in the evening before you go to bed. You will also complete an evening diary entry.

Monday Morning through Wednesday Morning: Each morning, as soon as you wake up, you will press the button on the sleep watch and take your first saliva sample. You will then complete a morning diary, take your 2nd saliva sample 30 minutes after the first, and complete the cognitive tasks on the iPod.
On Monday and Tuesday evening, you will complete the evening diary, take a saliva sample, and press the watch before you go to bed. You do not need to complete a diary or sample on Wednesday evening.

Wednesday Evening and Thursday: If you forget to perform any of the study tasks on Saturday through , then you can use Wednesday evening through Thursday morning to make up for any missed tasks. It is very important that you do these daily diary instructions on time each time. On Thursday morning, you will return all of your study items to the school.

Detailed Instructions

Step 1: **AS SOON AS YOU WAKE UP, AND BEFORE YOU GET OUT OF BED, EAT OR DRINK: Pool saliva in your mouth.** If your mouth is dry, chew the end of a straw briefly. This should make your mouth water. DO NOT swallow the saliva or spit it out.
*Remember to press the button on your watch until it shows a 1 when you wake up!

Step 2: **Open the plastic bottle and remove a straw, and take a vial from the bag marked "Vials."** Please always store the straws in the container and only open the container at times you are taking a sample. Open the container only once for each sample and close it completely when you're finished.

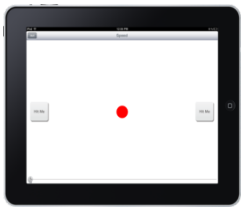
Step 3: **Put one end of the straw into the plastic vial, and the other end of the straw in your mouth.** Release the saliva from your mouth into the straw so that it flows into the vial. Try to fill the tube **one third** of the way full (if you cannot fill it that much, don't worry and just fill it as much as possible!). Be careful to hold the vial firmly; it can slip. **Screw the cap on the tube tightly so it will not leak.**

Step 4: **Label the vial.** Write down your ID number and the exact time and date on the appropriate label ***before*** you stick it on the vial, and ***then*** attach it to the vial**. It is very important that you record the date and time of each sample**. Place sample in the plastic bag labeled "Completed Samples."

Step 5: **Start the digital timer.** As soon as you write the exact time and date on your first vial, press the button on the timer sent in your kit, which is pre-set for **30 minutes.** *Please don't eat, drink, or brush your teeth while the timer is counting down.*

Step 6: **Complete the Morning Diary Entry.** While you wait for 30 minutes to take your 2nd morning sample, complete a morning diary entry in the booklet provided for you.

Step 7: **When the timer goes off, take your "Wakeup + 30 min" sample.** Once again, remove a straw from the plastic container and a vial from the bag, and spit into the vial. Record the exact date and time on the label. Put the label on the tube and put the tube into the bag labeled "Completed Samples"



Step 8: **Complete your iPod cognitive tasks.** Immediately after completing your Wakeup + 30 minute saliva sample, turn on the iPod as instructed on Saturday, and tap the Cities Project icon (it is a purple icon, shaped like a head!) on your device to activate the set of tasks. If the icon isn't visible, drag your finger from right to left across the screen and it should show up. **You will be asked for a Subject ID and Password – please type your full Cities Study ID number for both!** *Please see the*

Frequently Asked Questions section below for answers to common questions about the iPod cognitive tasks.

Step 9: **Refrigerate your sample!!!** As soon as you can after the iPod tasks, put the "Completed samples" bag in your fridge in a place where no one will disturb them. Add all samples to the Completed Samples bag in your fridge immediately after you take them.

Step 10 (in the evening): **Complete the online Evening Diary Entry.** Shortly before you go to bed, remember to complete the online evening diary entry. A link for this entry will be sent to your email each day, at around **6PM EST.** If you prefer to complete the evening diary on paper, please use the paper version provided to you."

Step 11 (evening): **Take your "Bedtime" sample**. Repeat Steps #2, 3 & 4 immediately before you go to sleep for your "Bedtime" saliva sample. If you brush your teeth right before going to bed, take your bedtime sample *before* you brush your teeth.

Step 12: Remember to press the button on your watch until it shows a 1 when you are ready to go to sleep!

Wednesday morning (after morning saliva samples and morning cognitive tasks):

Great job! You've completed the daily diary study! If you missed any saliva samples, please make them up Wednesday evening and Thursday morning, at the same times as your missed samples! You can use the FAQ section in the back of this book to determine which samples to make up, based on which ones you missed.

***Thursday Morning: Today, remember to bring all of your materials with you to school*!** Please pack everything in the black Cities Study bag provided. Please complete the checklist below as you pack your bag, to be sure that you are returning all the study materials and can receive your diary study participant payment and be entered in our iPod lottery!

Bag-Packing Checklist: Please place a checkmark next to each item as you pack it!

- □ All of your saliva samples from your fridge (stored in the "Completed Samples" bag)
- □ All of your Morning & Evening Diary booklets (blank and completed)
- □ Small plastic, orange container (that held the straws)

- □ Sleep watch (please put the watch back inside the zipper pouch)
- □ iPod (please put the iPod back inside the zipper pouch)
- □ Digital Timer

Frequently Asked Questions

Saliva Sampling

Q: I missed taking one of my samples, what should I do?
A: If you missed a sample on one day, please do a make-up sample according to the instructions below:

- Missed Wakeup sample → do a Wakeup and Wake+30 sample on Thursday
- Missed Wake+30 sample → do a Wakeup and Wake+30 sample on Thursday
- Missed an Evening sample → do an Evening sample on Wednesday

Also remember ***to keep your sleep watch on*** during the day(s) you complete your makeup samples!

Q: What if I wake up in the middle of the night? Does this count as waking up? Should I take a sample?
A: No, please take the samples in the morning when you actually plan to get up for the day.

Q: Where should I store my samples?
A: Please store you samples in the refrigerator in the "Completed Samples" bag. Make sure to tell your family what they are and why they're in the fridge so they don't throw them away! If you can't put your samples in the fridge right away, please make a note in the Comments section of your Evening Diary.

Q: Does it matter if I forget to write the time on the label of the vial?
A: Yes! It's really important for us to know the date and time you took your samples. If you do forget, please write down your best guess and write "est." (for "estimated") on the label.

Diary Entries

Q: I didn't do my morning or evening diary today, what should I do?
A: If you miss a Morning Diary, please fill it out by the evening of the same day. If you are unable to do that, please skip the diary entry completely. If you miss an Evening Diary, please fill it out by noon (12pm) the next day. If you are unable to do that, please skip the diary entry completely.

Sleep Watch

Q: Do I have to wear the watch at all times?
A: Yes, please wear the watch at all times from Saturday night to Wednesday morning. You should also keep the watch on if you are taking any make-up saliva samples on

Wednesday or later. Only take it off if you take a bath or go swimming or diving (wearing it in the shower or while doing the dishes is fine).

Q: My watch looks like it isn't working. Is it?
A: Yes, it's always working, even though it looks like it's off. As long as the screen flashes "--, 0, 1" when you push the button three times, it's working!

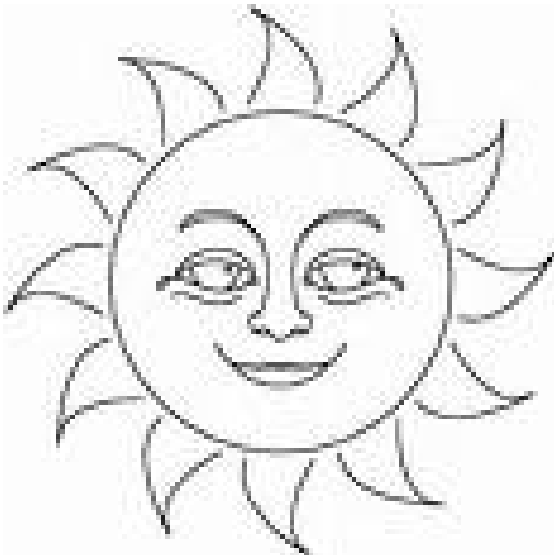
iPod Tasks

Q: I know how to do the tasks now – why do I have to do a practice trial every time?
A: Some people need to be refreshed on the rules of the tasks, and we want everyone to have exactly the same amount of practice so that everyone has exactly the same changes of doing well.
Q: I don't remember my Subject ID and Password – what are they?
A: You type your full Cities Study ID number for both your username and password. Your Cities Study ID number is written on the outside of your Saliva Sampling Kit. If you have trouble logging in, please contact us immediately.
Q: Can I quit the tasks and return to them later?
A: Yes, you can quit the task and return to it a few minutes later, but all of the tasks should be completed close together, and in the morning, within the first hour after waking. If you miss the tasks one morning, please complete an additional set of iPod cognitive tasks on Thursday morning before returning the device to school.
Q: Can I do the tasks more than once today?
A: We know the tasks are fun, and you'd like to try them again, but you can only do the tasks once each day. We want everyone to have the same amount of practice on the tasks.
Q: I love my iPod – can I keep it for a while and return it week or two later?
A: No, unfortunately we need to use all the iPods every week in our study. We have JUST enough iPods for the students that are participating each week, so please return your iPod on time so that other students can participate. Each iPod should be returned on the Thursday after you visited DePaul, immediately after completing the diary study. There is another good reason to return it on time – if you do, you will be entered in a lottery with TWO chances to win an iPod touch. If you return it late, you are only entered with ONE chance to win your own iPod touch. You also won't receive your subject payment until you return your diary study equipment.

Morning Daily Diary

DePaul Youth Stress Study

Daily Morning Diary



ID Number:

DAY 1: Please fill out this diary entry immediately after you take your "wakeup" saliva sample.

DATE:_____ TIME:_____ AM / PM

What time did you go to bed last night? _____ AM / PM

What time did you wake up this morning? _____ AM / PM

How long did it take you to fall asleep? ____hours ____mins

How much time were you awake during the night? ____hours ____mins

Please note the **number of times** you woke up during the night due to:

a. Noises	☐
b. Bad dream(s)	☐

c. Need to use the bathroom ☐

d. Just woke up ☐

e. Person or pet ☐

f. Too hot or too cold ☐

g. Too much light in room ☐

d. Physical discomfort or pain ☐

h. Other (please specify: ☐

_____

Did anyone else sleep in the same room with you last night? Yes No

If yes, how many people? _____ Adults _____ Children

Did you share a bed with anybody last night for all or part of the night?

Yes No

If yes…How are they related to you (e.g. pet, parent, sibling, friend, boyfriend/girlfriend, child)?_____

Was there anything unusual about your sleeping arrangement last night?

No Yes (please describe)_____

_____

Think about your sleep last night:

How well did you sleep last night?

1 2 3 4 5

Not At All Extremely Well

How well rested did you feel this morning?

1 2 3 4 5

Not At All Extremely Well

Did you sleep throughout the time allotted for sleep?

1 2 3 4 5

Woke Much Too Early Slept Through the Night

How easy was it for you to wake up?

1 2 3 4 5

Very Easy Very Difficult

How easy was it for you to fall asleep?

1	2	3	4	5
Very Easy				Very Difficult

Think about your upcoming day:

How challenging do you expect today to be?

1	2	3	4	5
Not At All				Extremely

What is the biggest challenge you expect to face today?

_____

Do you feel you can handle today's challenges?

1	2	3	4	5
Not At All				Definitely

Why or why not?

_____

Comments?

_____

_____