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Crochiere, R.J. orcid.org/0000-0003-2383-158X, Butryn, M.L., Zhang, F. et al. (5 more authors) (2024) Intraday relations between physical activity and energy intake among behavioral weight loss participants. Health Psychology, 43 (5). pp. 376-387. ISSN 0278-6133

https://doi.org/10.1037/hea0001358

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Intraday relations between physical activity and energy intake among behavioral weight loss participants

Rebecca J. Crochiere[a], **Meghan L. Butryn**[b,c], **Fengqing Zhang**[c], **Kristine Beaulieu**[d], **Jaclyn P. Maher**[e], **Zhuoran Huang**[b], **Clev Cong**[b], **Evan M. Forman**[b,c]

[a]Department of Psychology, Williams College

[b]Center for Weight, Eating, and Lifestyle Sciences (WELL Center), Drexel University

[c]Department of Psychological and Brain Sciences, Drexel University

[d]School of Psychology, University of Leeds

[e]Department of Kinesiology, University of North Carolina Greensboro

Abstract

Objective: Weight loss results from a negative energy balance, when energy intake (EI) is less than energy expended, e.g., from physical activity [PA]. However, PA may impact energy balance beyond energy expenditure alone, through indirect effects on eating behavior. Yet, no research has examined if engaging in PA—a central component of most weight loss programs—is associated with same-day EI among individuals with overweight/obesity pursuing weight loss.

Methods: Adults (*N*=101) with overweight/obesity in a weight loss program were prescribed a reduced-calorie diet and PA regimen (250 minutes of moderate-to-vigorous PA at mid-treatment). For 3 weeks at mid-treatment, PA and EI were measured via an accelerometer and self-monitoring app, respectively. Multilevel models examined within-person relations between EI preceding PA (*"pre-PA"*), acutely following PA ("*acute post-PA*," the 2 hours following PA), in the time following the *acute post-PA* period ("*remaining time in day*"), and across entire PA days ("*full-day"*), relative to non-PA matched time periods.

Results: EI was higher in the *pre-PA* and *acute post-PA* periods. There were no reliable differences in EI during the *remaining time in day* nor across the *full-day* on PA days versus within-subject matched non-PA days. There also was insufficient evidence to suggest EI pre-PA, post-PA, or across entire PA days, relative to non-PA matched time periods, was associated with percent weight change.

Conclusions: Findings suggest that engaging in PA was associated with different within-person EI patterns compared to non-PA days, though there was little evidence to support that these patterns relate to weight change.

Correspondence should be addressed to Rebecca Crochiere (rjc4@williams.edu).
There are no known conflicts of interest to disclose.

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Abstract

La pérdida de peso es el resultado de un balance energético negativo, cuando la ingesta de energía (EI, por sus siglas en inglés) es menor que la energía gastada, por ejemplo, por actividad física [PA, por sus siglas en inglés]. Sin embargo, la PA puede afectar el equilibrio energético más allá del gasto energético, a través de efectos indirectos sobre la conducta alimentaria. Sin embargo, ninguna investigación ha examinado si la práctica de PA- un componente central de la mayoría de los programas de pérdida de peso- está asociada con la EI el mismo día entre personas con sobrepeso/obesidad que buscan perder peso.

A los adultos (N=101) con sobrepeso/obesidad en un programa de pérdida de peso se les prescribió una dieta baja en calorías y un régimen de PA (250 minutos de PA de moderada a vigorosa a mitad del tratamiento). Durante 3 semanas a mitad del tratamiento, se midieron la PA y la EI mediante un acelerómetro y una aplicación de autocontrol, respectivamente. Los modelos multinivel examinaron las relaciones intrapersonales entre la EI que precede a la PA ("pre-PA"), la que sigue a la PA aguda ("post-PA aguda", las 2 horas posteriores a la PA), en el tiempo posterior al período post-PA aguda ("período restante del día"), y en días completos de PA ("día completo"), en relación con períodos de tiempo coincidentes que no son de PA.

La EI fue mayor en los períodos pre-PA y post-PA aguda. No hubo diferencias confiables en la EI durante el resto del día ni durante todo el día en los días de PA comparado con los días sin PA asociados entre sujeto. Tampoco hubo evidencia suficiente para sugerir que la EI antes de la PA, después de la PA o durante días completos de PA, en relación con períodos de tiempo coincidentes sin PA, se asociara con un cambio porcentual de peso.

Los hallazgos sugieren que realizar PA se asoció con diferentes patrones de EI dentro de la persona en comparación con los días sin actividad física, aunque hubo poca evidencia que respalde que estos patrones se relacionen con el cambio de peso.

Keywords

physical activity; energy intake; weight loss; mobile health technology

Introduction

Overweight/obesity and weight control are typically conceptualized via energy balance: the difference between energy intake (EI; from food and beverage intake) and energy expenditure (e.g., from resting metabolic rate and physical activity [PA]). A positive energy balance results when energy consumed exceeds that expended, leading to weight gain and eventually, overweight/obesity. Conversely, weight control programs work by helping individuals achieve a negative energy balance to lose weight, specifically by consuming *less* energy than is expended, and subsequently a neutral energy balance to maintain that weight loss, by consuming approximately the same amount of energy as is expended. These programs achieve these energy balance modifications through: 1) decreasing EI via a reduced-calorie diet; 2) increasing energy expenditure via engagement in high levels of PA.

Although it is well-established that achieving a negative and neutral energy balance facilitates weight loss and maintenance, respectively, the specific impact of PA on weight

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control is complicated and not well-understood. For example, PA has been shown to have minimal to no effect on weight loss, unless maintained at very high levels (such as 225–420 min/week of moderate-to-vigorous PA [MVPA]; Swift et al., 2018), and its effects on weight loss maintenance have been mixed. Non-experimental studies show that participants who are successful in maintaining weight loss generally engage in high levels of PA (Unick et al., 2017; Wing & Phelan, 2005); however, experimental studies that randomly assign participants to different levels of PA have not found significant differences in long-term weight control outcomes (Fogelholm et al., 2000; Tate et al., 2007; Washburn et al., 2021). These surprising results may suggest there is a more complex relation between PA, overarching energy balance, and weight control beyond the *direct* impact of PA on energy balance in increasing energy expenditure.

It may be that PA impacts energy balance through same-day *indirect* effects on eating behavior. For example, PA may lead to subsequent reduced EI, as vigorous or high intensity PA has been shown to temporarily suppress appetite (King & Blundell, 1995; King et al., 1994). However, paradoxically, it also may be that PA *increases* EI (Blundell et al., 2020), in that individuals may experience a perceived need to replenish their body post-exercise or permissiveness to consume energy after expending it through exercise. Importantly, increased EI acutely following PA could negate or even reverse the positive effects of PA on energy balance among those seeking weight loss because changes in diet often have an outsized effect on energy balance as compared to changes in PA (Church et al., 2009; Swift et al., 2014; Tsai & Wadden, 2006). As such, if PA leads to even minor changes in same-day EI, those changes in EI may have a larger impact on energy balance than the energy *expended* via PA. Few studies have examined these granular, same-day relations between PA and EI among behavioral weight loss participants. In fact, although PA is a central component of most behavioral weight loss programs, no known research has investigated if PA acutely (defined as <2 hours post-PA, per Schubert et al., 2013) or semi-acutely (defined as ≤24 hours post-PA in this study) impacts EI among individuals pursuing weight loss, for whom findings elucidating antecedents of energy balance are critical.

Although no known studies have examined the same-day, prospective relations between PA and EI among free-living individuals with overweight/obesity pursuing weight loss, research has examined the acute/semi-acute influence of PA on EI in other contexts (e.g., laboratory-based settings) and samples (e.g., with body mass index [BMI] in the healthy range). Findings from these studies have been mixed (Donnelly et al., 2014), ranging from PA *increases* EI (Martins et al., 2007; Verger et al., 1994), to PA *reduces* EI (Kim et al., 2016; Ueda et al., 2009), to PA has *no influence* on EI (Martins et al., 2015).

Additionally, research has examined the mechanisms of the relation between PA and EI, particularly appetite, though these findings also have been mixed. For example, some research suggests PA enhances sensitivity of the appetite regulatory system (Beaulieu et al., 2016; Martins et al., 2008), suppresses hunger hormones (e.g., acylated ghrelin; Beaulieu et al., 2015; Broom et al., 2009; Hagobian et al., 2013), and stimulates satiety hormones (Larson-Meyer et al., 2012), which may lead to reduced EI. Nevertheless, other studies have found that PA leads to acute *increases* in self-reported appetite (e.g., Maraki et al., 2005; Verger et al., 1992) which may result in increased EI. Further, multiple studies have

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found that PA's appetite suppressant effects are fleeting (King & Blundell, 1995; King et al., 1994), lasting up to 1.5 hours post exercise (Douglas et al., 2017), which may make their impact negligible. Thus, it is unclear if PA has a positive or negative acute effect, or an effect at all, on appetite and/or EI.

Moreover, the methodological designs of existing studies contain certain limitations that fail to yield an understanding of how free-living PA influences same-day EI among individuals with overweight/obesity pursuing weight loss. Much of the existing literature has been conducted in laboratory settings, in which the intensity and duration of PA were determined by the researcher and eating behavior was susceptible to demand characteristics and participant reactivity; thus, these investigations may not provide accurate proxies for real-world relations between PA and EI. Additionally, the majority of these laboratory-based studies have used healthy-weight, young, and/or physically active participants (Donnelly et al., 2014) not explicitly pursuing weight loss. Certain studies have used more ecologically-valid approaches and examined the free-living associations between PA and EI among individuals with overweight/obesity in PA or weight loss interventions (e.g., Andrade et al., 2010; Jakicic et al., 2002); however, these studies have not used prospective designs, precluding an understanding of the temporal relation between free-living PA and eating behavior. There has been one secondary analysis of a larger behavioral weight loss study that examined the prospective relation between free-living PA and subsequent eating behavior among individuals with overweight/obesity pursuing weight control (Crochiere et al., 2020). While results indicated that PA reduced likelihood of subsequent "dietary lapse," i.e., non-adherence to a reduced calorie diet, interpretation is clouded by the fact that the dependent variable (dietary lapse) was self-reported and subject to participant interpretation.

Thus, there remains a critical gap in the literature examining the same-day relations between PA and EI among individuals with overweight/obesity pursuing weight loss. By using technology that can measure these variables in individuals' every-day lives, specifically accelerometers and a dietary self-monitoring app, this study examined ecologically-valid, temporal relations between engaging in PA and same-day EI. Although the primary focus of this study was the prospective relation between PA and subsequent EI, a related and relevant topic is changes in EI occurring *prior* to PA (versus non-PA), such as anticipatory effects. Individuals pursuing weight loss may use exercise to compensate for EI or consume more calories earlier in the day because they plan to "burn off" that EI later via PA. Also, PA may displace meals and snacks. As such, to comprehensively understand the interplay between PA and EI in the context of a behavioral weight loss program, it was important for the current study to examine their interrelations across the entire day, including prior to PA. Moreover, given EI strongly influences weight change, this study also investigated if EI deviations prior to PA, following PA, or across entire PA days (relative to non-PA) were associated with short- and/or long-term weight loss outcomes.

This study aimed to evaluate several specific hypotheses. Consistent with findings from the most applicable studies (Carels et al., 2001; Crochiere et al., 2020), we hypothesized that engaging in PA would lead to reduced EI in the 2 hours that follow PA ("*acute post-PA*") as compared to non-PA matched time periods. However, in accordance with evidence suggesting PA's appetite suppressant effects are short-lived, with no significant

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effect on overall same-day EI (King et al., 1994), we hypothesized that individuals would account for the reduced EI in the *acute post-PA* period by consuming a greater amount in the "*remaining time in day,*" i.e., the time following the 2-hour post-PA period. See Figure 1A for an illustration of the time periods relative to PA examined in the current study. From a theoretical standpoint, weight loss participants also may choose to engage in PA if they feel the need to "burn off" calories ingested. As such, we hypothesized that EI *"pre-PA"* (preceding PA) would be greater versus non-PA matched time periods. In addition, given some evidence to suggest that EI is increased (within-subject) on days when PA occurs (Stubbs et al., 2004; Whybrow et al., 2008), we hypothesized there would be greater within-subject EI on entire PA versus non-PA days ("*full-day*"). We also hypothesized positive associations between differences in EI post-PA, pre-PA, and across full PA days (relative to non-PA) and percent weight change.

Methods

Participants

Participants were adults with overweight/obesity participating in a larger parent study, Project Activate (ClinicalTrials.gov Identifier: NCT04337619), a year-long behavioral weight loss treatment (for more details, see: Forman et al., 2021). Project Activate was a clinical trial designed to examine the independent efficacy of three distinct components of mindfulness and acceptance-based behavioral treatment (mindful awareness, mindful acceptance, and values clarity) on weight loss over and above standard behavioral treatment. Initially, $N = 119$ participants enrolled in recruitment Waves 1 (began March 2020) and 2 (began October 2020); however, $n = 13$ dropped from treatment prior to the mid-treatment assessment. Thus, $N = 106$ active participants attended the mid-treatment (6-month) assessment in recruitment Waves 1 and 2, where data collection for the current study took place. Of note, there were four waves of recruitment, but Waves 3 and 4 were not included in this study because certain measurements, such as EI via MyFitnessPal Premium, were not collected.

Participants met several criteria to be eligible for the larger parent study, including: BMI in overweight or obesity range (25–50 kg/m^2), aged 18–70, ability to engage in PA, desire to lose weight, and willingness for the research team to contact a personal physician for clearance of participation in the program. Exclusion criteria included: having a medical or psychiatric condition that could pose a risk to the participant during the intervention, influence weight, or limit ability to comply with the program; recently changed the dose of a medication that could significantly change weight; history of bariatric surgery; weight loss of > 5% in the previous 3 months; pregnant, breastfeeding, or planning to become pregnant; and active participation in another weight loss program. To be eligible for the current study, participants also needed to complete aspects of the mid-treatment protocol, described below.

Procedures

All study procedures were approved by Drexel University's Institutional Review Board (IRB). For the parent study, all participants were screened by phone for preliminary eligibility and interest and then invited to an orientation session where they received detailed

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information about the study. At the subsequent clinic visit, eligibility was verified and informed consent obtained, after which, a baseline assessment was completed. Following the assessment, participants were randomized to one of eight treatment conditions (for more information on conditions, see Forman et al., 2021). All participants were provided with a year-long, 25-session group behavioral weight loss treatment and prescribed the same reduced-calorie diet and PA regimen, allowing for collapsing across conditions in the current study. Sessions met weekly for the first 11 sessions, bi-weekly for sessions 12–14, and then every 6 weeks for sessions 15–20, with sessions lasting between 45–90 minutes, depending on condition. Due to the COVID pandemic, the intervention and mid-treatment assessments for Waves 1–2 were delivered remotely via Zoom, and study materials, such as the Fitbit and scale, were mailed to participants' homes.

The program prescribed a reduced-calorie diet: participants ≤250lbs were prescribed between 1200–1500 calories (kcal) per day and those >250lbs between 1500–1800 kcal per day. Each participant set a personalized daily calorie target within those ranges. Participants were asked to monitor their dietary intake daily throughout treatment. At each session, participants turned in their dietary self-monitoring records to group leaders, who provided feedback designed to increase accuracy of monitoring. In Wave 1, participants used whichever tracking method they preferred, either an app or paper records, with the majority choosing the app MyFitnessPal. In Wave 2, all participants were required to use MyFitnessPal.

Participants also were prescribed a graduated PA regimen that reached its maximum level of 250 minutes of MVPA/week, specifically 50 minutes of MVPA on 5 days per week, prior to mid-treatment. The current study collected data during the mid-treatment assessment because participants had recently reached the maximum MVPA prescription, allowing for ample opportunity to capture PA bouts. Throughout treatment, participants were asked to monitor their PA by recording the number of days on which they engaged in MVPA, the duration of MVPA bouts, and the average number of minutes of MVPA across the week. Participants also reported whether they met their MVPA goal in group sessions. In addition, all participants had a study-provided Fitbit Charge 3 or 4 at the mid-treatment assessment, which they were instructed to wear at all times to measure PA and to charge it overnight as needed.

At the mid-treatment assessment, all participants were instructed to log their dietary intake via MyFitnessPal Premium (paid for by study), which offers additional features beyond the free version of MyFitnessPal, such as tracking the precise timing of eating episodes. Mid-treatment assessors instructed participants on how to use MyFitnessPal Premium and how to record the timing of each eating episode.

Participants were incentivized to comply with the MyFitnessPal Premium and Fitbit protocols. Participants had the opportunity to earn $150 over the 3-week period ($50 per week) for compliance with various aspects of the mid-treatment protocol. The compensation scheme was modeled after incentivization systems that have yielded high rates of compliance with sensor wear in the past (Crochiere et al., 2021). Participants were informed they would experience deductions of $1 for instances of non-compliance, which

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included not providing the timing of eating episodes in MyFitnessPal Premium, logging <2 meals/snacks or <500 kcal daily (deemed incomplete reporting), or not wearing or charging the Fitbit. If participants provided no MyFitnessPal data or no times of meals/snacks on a day, the deduction was $5 (based on ~5 eating episodes or 3 meals and 2 snacks daily). A data monitoring protocol to shape compliance involved frequent monitoring and participant contact in the first few days of the protocol, which became less frequent and intensive over time.

Measures

Energy intake (EI)—EI was operationalized as the total energy content of food and beverage consumed, measured in kcal. MyFitnessPal's EI estimates have been shown to be accurate, underestimating daily EI by only 30 kcal (Chen et al., 2015) and correlating strongly ($r = 0.93$; Griffiths et al., 2018) with EI in the Nutrition Data System for Research (NDSR) (Dennis et al., 1980). Additionally, accuracy of dietary self-monitoring may be enhanced in a gold-standard behavioral weight loss program, which provides: instructions that participants weigh and measure their food and beverage intake whenever possible, training in portion size estimation, and supportive accountability to group leaders and research staff who monitor dietary reporting (Martin et al., 2007). A valid day (those used in analyses) required participants to have logged ≥2 eating instances and ≥500 kcal. If the time of a meal/snack was missing, the mean time of the meal/snack was imputed by participant. For example, if the time of lunch was missing for Participant A, the average time Participant A ate lunch was imputed.

Energy intake (EI) deviation—Within-person EI deviation was calculated by: 1) taking the difference between EI consumed during specific time periods on PA days (*pre-PA, acute post-PA, remaining time in day,* and *full-day*) versus EI consumed during accompanying non-PA matched time periods, and 2) then dividing the difference by average daily EI. This created a within-person percent increase or decrease in EI occurring on PA days.

Physical activity (PA)—Participants wore a Fitbit Charge 3 or 4 for the 3-week mid-treatment assessment. As compared to research-grade accelerometers, Fitbits have shown superior compliance and near-equivalent accuracy in measuring PA (Brooke et al., 2017). The Fitbit determines the intensity of PA through metabolic equivalents (METs), taking into account body mass and the rate of energy expenditure during activity versus rest. Fitbit categorizes PA as lightly active (1.5–3 METs), fairly active (3–6 METs), or very active (6+ METs) (Semanik et al., 2020), which are equivalent to light, moderate, and vigorous intensity PA, respectively; the latter terminology will be used henceforth. Although the program prescribed MVPA, other gold-standard behavioral weight loss programs have found that participants more often engage in light PA than MVPA at mid-treatment (Crochiere et al., 2020). The current study thus aimed to examine the relations between EI and both MVPA and all free-living PA (henceforth called "any-intensity PA," including light PA, such as activities of daily living and non-exercise PA). Study aims were tested using each definition of PA, and references to PA refer to both types of PA. Fitbit data were collected at the minute level through the Fitbit API Intraday feature. A valid day (used in analyses) required ≥10 hours of Fitbit data (based on steps occurring in ≥10 hours of the day).

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Moderate-to-vigorous PA (MVPA) bouts.: Existing research has defined a MVPA bout as at least 10 consecutive minutes in which 80% of the minutes are at or above the moderate level of intensity (e.g., Clark et al., 2019; Menai et al., 2017; Strath et al., 2008). For this study, a similar definition was used, but the minimum number of minutes was increased to 30 to enhance the ability to test study aims, specifically to ensure there were enough days on which *no* PA bouts occurred to allow for sufficient non-PA matched time periods. Therefore, MVPA bouts contained ≥30 continuous moderate or vigorous minutes, with limited allowances of interruptions below the moderate threshold, such that 80% of the minutes were at or above the moderate level. Using this threshold, approximately 42% of participant days captured an MVPA bout, allowing for a sufficient number of PA and non-PA matched controls.

Any-intensity PA bouts.: Similar standards were used to operationalize any-intensity PA bouts. Any-intensity PA bouts were defined as ≥60 continuous light, moderate, or vigorous minutes, with limited allowances of interruptions below the light activity threshold (or sedentary minutes), such that 80% of the minutes within the 60-minute block were at or above the light activity level. Because light PA was included in this PA bout definition, the 30-minute time frame used for MVPA was deemed too liberal in that there may be many 30-minute periods in which 80% were light PA, which would severely limit non-PA matched controls. As such, the minimum number of minutes was doubled from MVPA to enhance the stringency of the PA measurement and the amount of usable data to test study aims. This definition also was informed by data illustrating that even when behavioral weight loss participants are prescribed a MVPA prescription of 50 minutes on 5 days per week, they more often engage in light PA than MVPA (Crochiere et al., 2020). As such, this definition, which captures at least 48 minutes (80% of 60) of light, moderate, or vigorous PA, aligns well with the type of PA that study participants typically engage in. Additionally, using this threshold, approximately 48% of participant days captured an any-intensity PA bout, allowing for a sufficient number of PA and non-PA matched controls.

Body weight—Participants weighed themselves using study-provided Bluetooth wireless scales, either Eufy or Fitbit Aria scales, in Waves 1 and 2, respectively. Throughout treatment, participants were asked to weigh-in weekly, first thing in the morning, prior to eating, after having used the bathroom, and with shoes and/or extra clothing removed. Participants followed similar instructions when providing assessment weights, but did not necessarily weigh-in first thing in the morning due to variable timing of assessments. As such, steps were taken to increase accuracy of body weight measurements (see below).

Percent weight change—Percent weight change from a) baseline to mid-treatment and b) the beginning to the end of the 3-week mid-treatment assessment were computed by subtracting the earlier weight from the later, dividing by the earlier weight, and multiplying by 100. Mid-treatment assessments were conducted at various times during the day to accommodate participant schedules, such as in the afternoon or evening, non-optimal times at which to measure weight due to EI throughout the day. Thus, to arrive at more accurate estimates of the mid-treatment assessment weight (Day 0) and end-of-mid-treatment assessment weight (Day 21), all available weights (both official and from Bluetooth weigh-

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ins) from 3 days prior to and 3 days after these target dates were averaged. Following this procedure, there was *n* = 1 missing weight from the mid-treatment assessment and *n* = 3 missing weights from the end-of-mid-treatment assessment. Little's Missing Completely at Random (MCAR) Test showed these data were missing at random p>.05. Regressions using weights from 4–7 days prior to and 4–7 days after each target date were used to impute the weights 3 days prior to and 3 days after the target dates. Then, all weights from 3 days prior and 3 days after the target date were averaged to arrive at a weight estimate.

Data Preparation

PA bouts were identified using Python. As detailed in Figure 1, the "end of day" was determined to be 4:00am, given that late-night eating can occur after 11:59pm. As such, the *pre-PA* period started at 4:01am and continued until the beginning of the PA bout (e.g., if a PA bout went from 7:30am-8:30am, the *pre-PA* period went from 4:01am-7:29am). The minute following the end of a PA bout represented the beginning of the 2-hour *acute post-PA* period (e.g., if PA ended at 8:30am, the *acute post-PA* period went from 8:31am to 10:31am) and the *remaining time in day* period began in the first minute following the end of the *acute post-PA* period, ending at 4:00am the next day (e.g., 10:32am-4:00am the next day).

To best test study aims, PA days needed to meet certain criteria to be included. Aims examining the relation between PA and EI in the *pre-PA* and *acute post-PA* periods included only the first PA bout of the day, as subsequent bouts may be confounded by hypothesized post-PA effects. In addition, if a subsequent bout occurred within the *acute post-PA* period after the initial bout, that day was not included in analyses, due to potential confounding effects. For the *remaining time in day* analyses, only PA days with a single PA bout were used as multiple PA bouts may introduce confounding effects by re-instigating hypothesized effects in the *acute post-PA* period. All PA bouts were only included in analyses if there existed a non-PA matched control associated with them (see below). *Full day* analyses included all days with PA, including multiple PA bouts.

Matched controls were identified using Python, such that the code identified the participant ID, start time, and end time of the PA bout and then ran a loop through that participant's data to find matched non-PA controls, which also matched the weekday/weekend status of the PA counterpart. All possible within-person non-PA matched controls were used. For example, if there were 4 usable non-PA matched controls for 1 PA day, all 4 controls were included in analyses. Nevertheless, non-PA matched controls needed to meet specific criteria to be included. For the *pre-PA* and *acute post-PA* aims, controls needed to have no PA occurring prior to or during the *acute post-PA* window, to prevent confounding post-PA effects on EI (see Figure 1B). It is possible that these matched controls were still confounded by additional PA bouts that occurred following the *acute post-PA* window in the *remaining time in day*. To test for this potential confound, the primary aims were run two ways: 1) with matched controls that have no PA prior to or during the *acute post-PA period* and 2) with matched controls that were *full* non-PA days. The pattern of results was the same; as such, the former was used to allow for a greater number of matched controls. For the *remaining time in day* analyses, non-PA matched periods were *full* non-PA days to prevent confounding effects of PA on EI (see Figure 1C). This approach of selecting non-PA

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matched controls allowed for within-person comparison of EI occurring in the *pre-PA*, *acute post-PA*, and *remaining time in day* on PA days to EI occurring in the *exact same time periods* on non-PA days. Participants who lacked non-PA controls were removed from analyses.

Data Analyses

SPSS vs.27 and R v.4.2.2 were used to conduct analyses. Relations were examined between several potential control variables and the key study variables, average daily EI and PA. There were no meaningful, significant differences in daily EI nor PA by: condition, wave, prior MyFitnessPal use, nor race; therefore, these variables were not controlled for. There *were* meaningful, statistically significant differences in daily EI and/or PA by gender (EI: $t(97) = 3.76$, $p < .001$), age (EI: $r = -.35$, $p < .001$), and BMI (PA: $r = -.41$, $p < .001$); thus, these three variables were controlled for in person-level analyses.

Aims examining the within-person relations between PA and EI were analyzed using multilevel modeling. For these analyses, PA versus non-PA was the binary independent variable. Of note, multilevel models require at least one valid PA and one valid non-PA day. All continuous predictors were standardized. Restricted maximum likelihood was used to estimate model parameters and to test the significance of random effects. Models were fit using the R package *lme4* (Bates et al., 2015). The lower level, or level one data, was PA versus no PA. Level one data were nested within the level two unit, participant. Model selection criteria such as Akaike information criterion (AIC) and ANOVAs were run to determine whether a model with a random intercept or random intercept plus random slope better fit the data. Models used both a random intercept and slope when ANOVAs indicated a better fit with this model structure, though some models used only a random intercept, which is noted when applicable. Including whether a day was a weekday/weekend allowed for control of this variable's variance. Residual plots were visually inspected to ensure normality, homoscedasticity and absence of outliers, and multicollinearity was not a concern (variance inflation factors <2.0). Unstandardized *b* values are reported throughout the results. Aims testing the relation between EI deviation on PA versus non-PA days and weight change were tested using multiple linear regressions, controlling for BMI, age, and gender.

Results

Participants

Participants were those who had not dropped from treatment in Waves 1 and 2 and attended the mid-treatment assessment ($N = 106$). Five participants were excluded from analyses due to: refusal to use MyFitnessPal ($n = 1$; preferred paper records); refusal to use both MyFitnessPal and Fitbit ($n = 1$), technical difficulties with MyFitnessPal or Fitbit ($n = 2$), and insufficient MyFitnessPal data due to non-compliance ($n = 1$). The $N = 101$ participants included in analyses were predominately female (85.1%), White/Caucasian (69.3%), middle-aged, and classified with overweight/obesity. See Table 1 for more detailed descriptive statistics. Of note, participants excluded from analyses did not differ from those included on key demographics (all p's > .05).

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Data Completeness

Across participants, there were 1,797 days of Fitbit wear, of which 0.9% (*n* = 17) were considered non-wear days and were excluded from analyses, resulting in Fitbit compliance of 99.1%. Participants logged 9,990 meals/snacks logged in MyFitnessPal, of which 3.3% (*n* = 329) were missing the time of the meal/snack. Of 1,984 participant days, 1.6% (*n* = 31) had <500 kcal logged and 1.2% (*n* = 24) had <2 meals logged, which were excluded due to the likelihood that they represented underreporting.

As mentioned above, at least 1 PA day and 1 non-PA day per participant were required to estimate the contrast between PA and non-PA days at the individual level. For *pre-PA* and *acute post-PA* analyses, *n* = 10 and *n* = 4 participants were excluded from MVPA and any-intensity PA analyses, respectively (MVPA: *n* = 10 did not have at least 1 MVPA bout; Any-intensity PA analyses: *n* = 3 did not have at least 1 PA bout; *n* = 1 did not have a non-PA matched control). As such, there were 625 MVPA bouts across 91 participants and 735 any-intensity bouts across 97 participants for these analyses. For *full-day* and *remaining time in day* MVPA analyses, *n* = 13 participants were excluded (MVPA: *n* = 9 had no MVPA days; *n* = 4 had no *non*-MVPA days). As such, there were 88 participants in these analyses, with 500 MVPA bouts in the *remaining time in day* and 690 days with MVPA bouts in the *full-day* analyses (*full-day* analyses allowed for multiple PA bouts per day, resulting in more eligible days). For *full-day* and *remaining time in day* any-intensity PA analyses, *n* = 8 and *n* = 7 participants were excluded, respectively (*n* = 5 had no days *without* PA; the remainder had no days *with* PA). As such, there were 93 participants with 526 any-intensity PA bouts in the *remaining time in day* analyses, and 94 participants with 836 days with any-intensity PA bouts in the *full-day* analyses. Of note, participants excluded did not significantly differ from those analyzed on key demographics (*p*'s > .05).

Descriptive Statistics

Table 1 provides descriptive statistics of participant characteristics (as mentioned above) and key study variables, including EI, PA bouts, EI deviation, and percent weight change.

Main Effects

See Figure 2 for an illustration of EI prior to and post PA relative to non-PA matched time periods. Consistent with hypotheses, EI was increased *pre-PA* versus non-PA matched time periods, such that on average participants consumed approximately 61 and 88 more kcal prior to MVPA and any-intensity PA, respectively (Table 2). Contrary to hypotheses, engaging in PA was associated with increased EI in the *acute post-PA* period compared to non-PA matched periods, such that on average, MVPA and any-intensity PA engagement was associated with consuming approximately 35 and 26 more kcal, respectively (Table 2). In addition, contrary to study hypotheses, there was insufficient evidence to support that: 1) PA was reliably associated with increased EI in the *remaining time in day*; 2) PA was meaningfully associated with increased *full-day* EI (Table 2).

EI deviation and weight change

There was little evidence to suggest EI pre-PA, post-PA, or across entire PA days, relative to non-PA matched time periods, had a relation with percent weight change (see Table 3).

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Discussion

Weight control is determined by energy balance and tends to be more strongly influenced by EI than by PA, but no known research prior to the current study had examined the relation between PA, a central component of most behavioral weight loss programs, and same-day EI among individuals with overweight/obesity seeking weight loss. Given evidence to suggest PA leads to short-lived appetite suppression (King & Blundell, 1995) and reduced likelihood of overeating among those pursuing weight control (Crochiere et al., 2020), it was hypothesized that PA would result in *reduced* EI acutely following PA, followed by a period of overcompensation or *increased* EI in the remaining time in the day. However, contrary to hypotheses, EI was slightly higher acutely following PA and did not differ in the remaining time in the day post-PA relative to non-PA matched time periods. Consistent with the hypothesis that there would be anticipatory effects of PA on EI, EI was *higher* prior to PA relative to non-PA matched time periods. There were no meaningful or reliable differences in full-day EI on PA versus non-PA days, contrary to hypotheses. As such, although EI seemed to be affected or displaced by PA, overall daily EI was comparable on PA versus non-PA days.

Increased EI acutely following PA was unexpected due to supported mechanisms like acutely suppressed appetite post-PA, which in turn can reduce EI. Nevertheless, the acute appetite suppression effect has been shown to last approximately 1 to 1.5 hours (Bellisle, 1999; Douglas et al., 2017; King & Blundell, 1995), and the acute 2-hour post-PA period may have outlasted the short-lived appetite suppression effect, potentially capturing subsequent overcompensation of EI in the final 30–60 minutes of the 2-hour post-PA period. Even more nuanced investigations may help to elucidate if the appetite suppression effect is operative but fleeting for this population. Extant studies also have measured these appetite suppressant effects via perceived appetite ratings versus actual EI post-exercise. It may be that, regardless of perceived appetite post-PA, behavioral weight loss participants use eating as a “reward” for engaging in PA or *expect* to be hungry after PA (despite perhaps not experiencing physiological hunger), which leads to increased EI post-PA.

Increased EI in the acute post-PA period also seemingly conflicted with findings from studies with similar methodological designs and samples. Specifically, two studies examined the intraday relation between PA and dietary lapse (dietary non-adherence) among behavioral weight loss participants and found that PA acutely *reduced* likelihood of subsequent dietary lapse (Carels et al., 2001; Crochiere et al., 2020). However, there are several potential reasons for the discrepant findings. These studies relied on participants’ perception of whether they lapsed, which may have been biased by engagement in PA; for example, one may not perceive a calorie overage as a lapse because one just “burned” calories through PA. This especially might be the case given that the observed increase in acute EI in the current study was relatively small, on the order of 2% of the samples’ average daily EI and thus easy to discount as insubstantial. Additionally, the current study measured EI in a precise 2-hour period following PA, whereas previous studies like Crochiere et al. (2020) examined risk of lapse in the 2–3 hours following PA, potentially spanning both the acute and remaining time in the day periods, making it difficult to directly compare findings. Also notably, Crochiere et al. (2020) found risk of lapse was reduced following light PA, but

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not MVPA, which was not examined in the current study. Thus, it remains possible that light PA specifically is associated with reduced EI acutely following PA.

Results did not support the hypothesis that there would be reliable differences in EI in the remaining time in day on PA days versus non-PA matched controls. The effect size of MVPA on EI in the remaining time in day was comparable to that of the acute post-PA effect (though with opposite directionality), but included more variability, which may have precluded our ability to detect a significant effect.

It was hypothesized that EI would be increased prior to PA versus non-PA matched controls due to compensatory effects, specifically that weight loss participants may choose to engage in PA if they feel the need to "burn off" calories ingested earlier in the day. Overall, main effect findings were consistent with this hypothesis, showing marginal but meaningful increases in EI prior to PA, with participants consuming approximately 61 and 88 more kcal (4–6% of their average daily intake) prior to MVPA and any-intensity PA, respectively, compared to matched non-PA time periods. In addition to compensatory effects, increased EI prior to PA may be due to anticipatory effects, such as wanting to fuel or energize one's body prior to engaging in PA. Alternatively, PA may displace meals/snacks, such that individuals eat a meal earlier than is typical to accommodate PA, resulting in elevated EI prior to PA.

Results did not support the hypothesis that there would be meaningful or reliable differences in full-day EI based on PA engagement. Although EI was *increased* prior to and acutely following PA, even when summed together, these increases in EI were relatively small compared to overall daily EI, on the order of 6–8%. Further, despite a large sample and sufficient statistical power, there was substantial variability in these effects, which may have precluded significant findings and may signal underlying individual differences or moderation effects in the relations between PA and same-day EI.

Study findings justify the importance of examining post-PA EI in a time-varying way, given that the relation between PA and post-PA EI depended on how much time had elapsed since PA. These findings are in contrast to much of the literature, which is mixed, but primarily concludes there is no difference in EI acutely following PA bouts compared to rest controls (Donnelly et al., 2014). There are several reasons to suspect that the current study's findings represent a more accurate picture of the acute effect of PA on EI in the context of study aims. First, existing studies have been limited by small sample sizes, with a systematic review reporting a median sample size of 12 (Donnelly et al., 2014), thereby likely lacking the statistical power to detect effects. In contrast, the current study had a large sample size ($N = 101$) and high-dimensional dataset, which was powered for the primary aims. Second, the existing literature almost exclusively has studied healthy-weight samples maintaining a neutral energy balance (Donnelly et al., 2014), whereas the current study examined a unique sample of individuals with overweight/obesity pursuing a negative energy balance, who likely regulate their eating behavior post-PA differently than do other populations. For example, behavioral weight loss participants may feel particularly hungry acutely following PA, given they are chronically limiting their EI and just expended energy during PA, which may lead to increased EI. Third, existing studies have been conducted

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in the laboratory, collecting data on a single PA observation, whereas the current study used several observations over time in an ecologically valid setting, likely reflecting more accurate real-world effects.

It also was hypothesized that *increased* EI prior to PA, post-PA, and across entire PA days, relative to non-PA matched controls, would be *negatively* associated with percent weight loss. There was little evidence to suggest that deviations in EI pre-PA, post-PA, and across entire PA days (versus non-PA matched time periods) had reliable relations with weight change. These findings are inconsistent with the literature, which has shown the degree to which an individual compensates for energy expended via PA can significantly impact weight loss outcomes (Church et al., 2009; King et al., 2008). The current study was not powered for these exploratory aims, which may have contributed to a lack of statistically significant findings.

Findings from the current study have implications for behavioral weight loss treatments. Results elucidated that PA, a central component of most behavioral weight loss programs, has a relation with same-day EI, which is the core driver of behavioral weight loss. These findings are clinically significant in that they suggest PA was associated with changes in EI, and for individuals with overweight/obesity pursuing weight management, changes in EI can have significant consequences on weight control efforts. Psychoeducation to behavioral weight loss participants about the overall patterns observed in the current study may help to raise awareness of "high risk" times of elevated EI, such as those occurring prior to and acutely following PA, which in turn allows for planning and problem solving to mitigate risk. More specifically, program leaders could educate participants about the tendency to increase EI prior to and acutely following PA and suggest skills to curb elevated EI, such as monitoring food intake carefully during these periods.

These results should be interpreted in the context of the study's limitations. This study prioritized acceptability when selecting measurement tools, choosing Fitbit and MyFitnessPal over measures with research-grade validity; as such, improvements in accuracy of measurement could be made. For example, the Fitbit has been shown to overestimate certain measurements, specifically energy expenditure, with moderate to large effect sizes (O'Driscoll et al., 2020). Similarly, self-reported dietary intake is notoriously flawed, and future research may explore more objective methods like doubly labelled water. Nevertheless, several measures were put into place to enhance the validity of self-reported dietary intake in the current study, including participants being trained in weighing/ measuring food and estimating portion size, and research assistants monitoring data in real-time to alert participants to potential underreporting. Also, although definitions of PA were based on the literature, specifically previous research defining a PA bout as at least 10 consecutive minutes in which 80% of the minutes are above a certain intensity point (e.g., Clark et al., 2019; Menai et al., 2017; Strath et al., 2008), the minimum number of minutes was increased to 30 for MVPA and 60 for any-intensity PA for study design purposes. This higher duration threshold for PA bouts may bias results in that only PA bouts of moderate-to-long duration were included, and those bouts may have more pronounced relations with same-day EI as compared to shorter bouts.

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Another limitation is that this project lacks the experimental control attained in laboratory settings and thus the ability to draw causal conclusions, given third variables could be explaining the relation between engagement in PA and EI. To an extent, the current study's design of examining momentary, within-person effects mitigates this issue, in that it controls for individual participant-level differences in third variables like motivation. However, this approach does not control for momentary third variables, such as differences in stress or mood on a given day that may lead to both engagement in PA and differential eating patterns for an individual. Future research could control for these state-level psychological variables, given their potential to influence the relation between PA and EI, and explore if these variables operate as mediators of the relation between PA and EI.

Additional limitations relate to the timing and length of the assessment period. The mid-treatment assessment period was used for the current study because it coincided with the maximum level of the treatment's graduated PA prescription (250 minutes of MVPA/week), allowing for ample opportunity to observe PA bouts. However, the mid-treatment assessment occurs 6 months into the behavioral weight loss program, such that participants experience less rapid weight loss than they do early in treatment due to several factors, including weight suppression, reduced motivation to lose weight, self-regulatory fatigue, or intentionally switching to weight loss maintenance. As such, weight change observed in the 3-week mid-treatment assessment period is limited as compared to that which might be observed at earlier phases in treatment, when participants are making significant changes to their diet, motivation to lose weight is high, and weight is not suppressed. Relatedly, a longer assessment period also would have allowed for more weight change, improving the ability to examine the relation between EI deviations based on PA and concurrent weight change. In addition, a longer assessment period may have allowed for all participants to attain the requisite number of PA and non-PA days to be included in analyses (at least one PA and one non-PA day), reducing the number of participants excluded for this reason. Finally, generalizability is limited by a homogenous (predominately white and female) sample.

This study also had notable strengths, including being the first to examine the temporal, intraday, time-varying relations between free-living PA and EI in an ecologically valid setting. Further, this study was the first to examine these relations among individuals with overweight/obesity pursuing weight loss, a population that stands to benefit significantly from understanding the relation between PA and EI, given most are attempting to achieve weight loss via high levels of PA and/or a reduced-calorie diet. Existing research in this area has primarily been conducted in the laboratory, which is subject to demand characteristics, experimenter control (e.g., over PA duration and intensity), and participant reactivity, and has used healthy-weight samples, rendering findings inapplicable to the aims of the current study.

Future research should build upon the current study's findings by using methodology that allows for more precision and confidence in testing a causal relation between PA and EI. For example, researchers could randomly assign days on which behavioral weight loss participants engage in PA versus not, controlling for potential third variables like motivation. Future research also may aim to replicate these findings by using other measurement tools such as research-grade accelerometers to measure PA and 24-hour dietary recalls to measure

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EI. Moreover, future research could examine pre- and post-PA intake on a more granular level, such as on an hourly basis, as the 2-hour mark delineating the acute post-PA and the remaining time in the day period is likely arbitrary.

Future research also should explore how various phases of weight loss could moderate the relation between PA and same-day EI. For example, participants typically experience high levels of motivation to lose weight at the initial phases of treatment, and therefore at that time, there may be attenuated increases in pre-PA or acute post-PA EI relative to that observed in the current study (which took place at mid-treatment), as individuals may be particularly intent on not “undoing” the hard work they put into PA, such as by consuming calories they just expended through PA. However, there are limitations to using the initial phases of treatment as well, including the typically low levels of PA prescribed by the graduated PA regimen early in treatment, such as no initial PA prescription or one day of PA a week, meaning there would be fewer opportunities to capture the relation between PA and same-day EI. Nevertheless, examining the relations between PA and same-day EI at the initial phases of treatment may produce unique findings that could have implications for behavioral weight loss programs.

Finally, the current study focused on overall EI, but understanding the ways in which PA may influence size of and/or frequency of meals/snacks, such as changes in portion size of meals/snacks or the number of eating episodes, may elucidate the mechanisms through which PA is associated with EI, which in turn could inform behavioral weight loss programming. Additionally, the current study focused on the relations between PA and EI within the same day, but it remains possible that behavioral weight loss participants engage in compensatory exercise the day following higher EI. As such, future research should explore these across-day, bidirectional relations between PA and EI. Moreover, given the significant variability observed in the relation between PA and EI, future research should investigate if individual differences or other variables moderate the relation between PA and same-day EI.

Acknowledgments

This research was supported by an R01 grant (R01DK119658; ClinicalTrials.gov Identifier: NCT04337619) to Dr. Forman from the National Institute of Diabetes and Digestive and Kidney Diseases. De-identified data and analytic code from this study are available (as allowable according to Institutional Review Board standards) upon reasonable request by emailing the corresponding author.

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Public significance statement:

This research project was the first to demonstrate that for behavioral weight loss participants, engaging in physical activity (PA) is associated with different patterns of same-day energy intake (EI), relative to not engaging in PA. Findings are significant because they indicate PA, a central component of most behavioral weight loss programs, is related to changes in EI, which is the core driver of weight loss. Behavioral weight loss programs may improve weight management outcomes by teaching participants skills to manage the EI fluctuations associated with PA.

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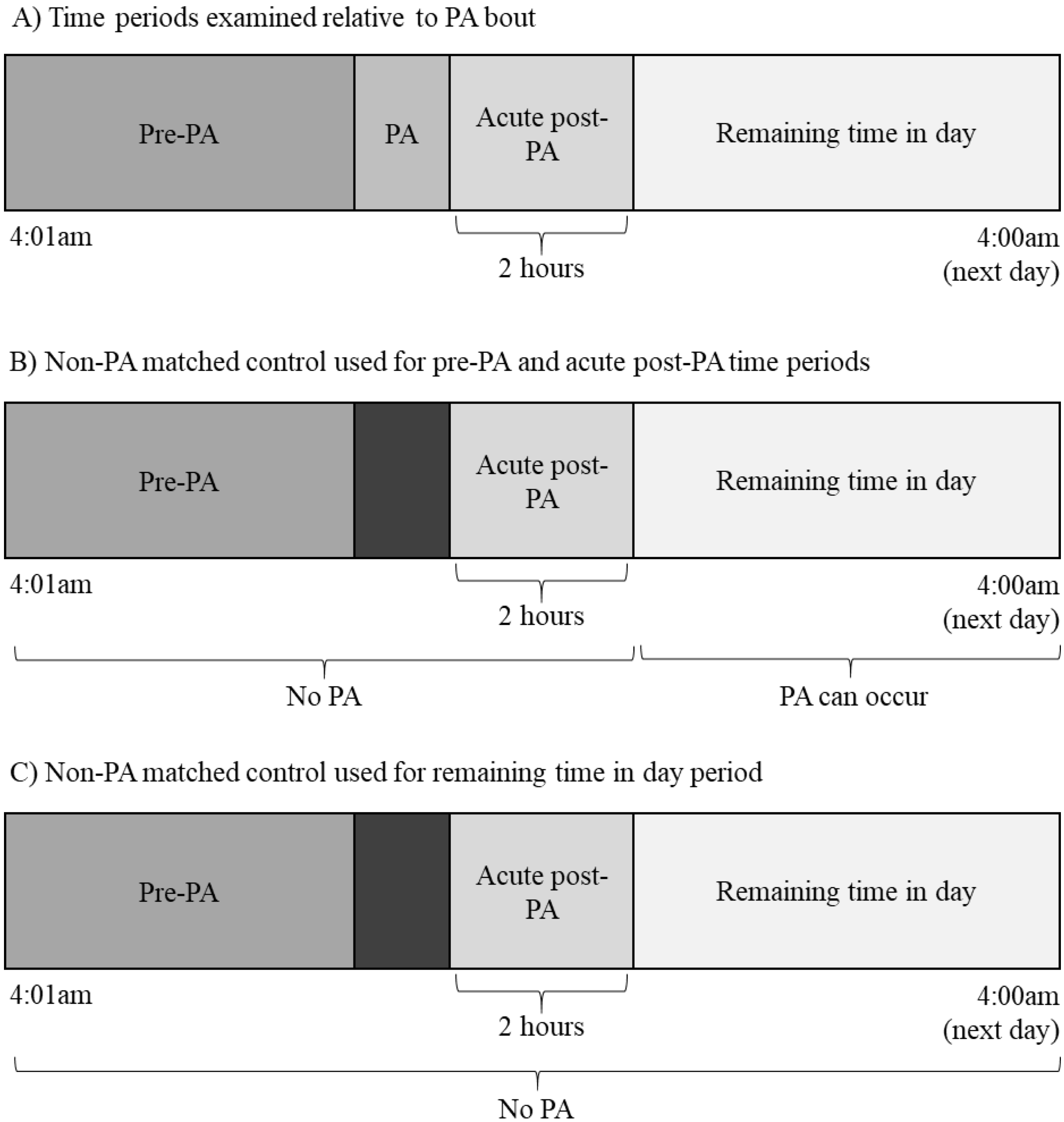

Figure 1. Time periods relative to physical activity (PA) examined in the current study

Note. The "end of the day" was determined to be 4:00am, as late-night eating can occur after 11:59pm.

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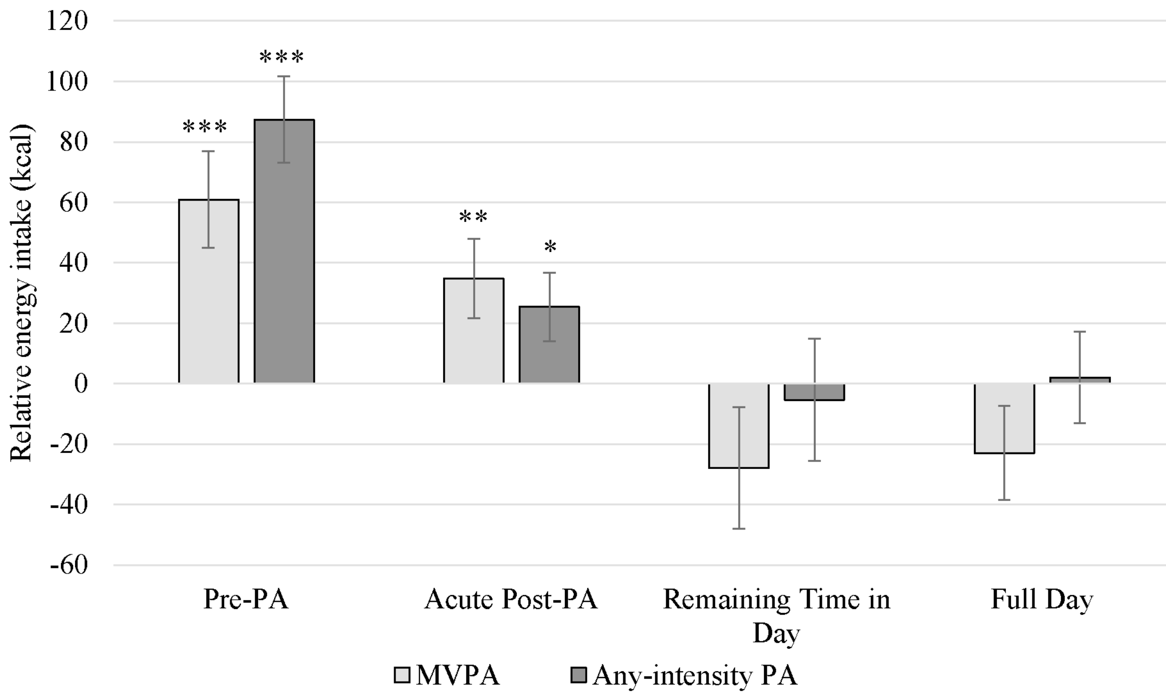

Figure 2. Energy intake prior to physical activity (PA), post-PA, and across full PA days relative to non-PA matched time periods

Note. *** $p < .001$; ** $p < .01$; * $p < .05$; PA = physical activity; MVPA = moderate-to-vigorous physical activity.

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Table 1

Descriptive statistics for key study variables

	N	%		
Participant Characteristics				
Female	86	85.1		
Male	15	14.9		
White/Caucasian	70	69.3		
Black/African/African American	26	25.7		
Asian	3	3.0		
Multiracial	2	2.0		
Unknown/No Response	1	1.0		
Hispanic	5	5.1		
	M	*SD*	*Min*	*Max*
Participant Characteristics				
Baseline BMI (kg/m^2)	35.5	5.4	27.1	49.1
Mid-treatment BMI (kg/m2)	32.1	5.9	23.0	47.2
Age	54.03	11.71	22.78	71.31
Dietary variables				
Daily EI (kcal)	1,380.14	412.99	501.10	3,752.00
MVPA bouts				
Active minutes per bout	44.05	28.65	24.00	242.00
Energy expended (kcal) per bout	356.70	286.33	119.75	2,560.26
Bouts per week	3.67	2.44	0.33	9.95
Any-intensity PA bouts				
Active minutes per bout	69.64	36.59	48.00	415.00
Energy expended (kcal) per bout	386.26	243.99	124.00	3,530.40
Bouts per week	4.57	2.98	0.35	12.16
MVPA EI deviation (%)				
Pre-PA	1.68	10.43	−19.89	41.77
Acute post-PA	0.97	10.87	−40.55	29.64
Remaining time in day	−2.20	13.14	−76.98	23.40
Full day	−1.14	12.44	−24.55	57.16
Any-intensity PA EI deviation (%)				
Pre-PA	3.37	10.45	−11.64	48.04
Acute post-PA	0.54	10.83	−61.37	30.19
Remaining time in day	0.81	12.37	−29.21	37.80
Full day	0.80	13.42	−29.13	57.16
Percent weight change				
Across 3-week mid-treatment assessment	−0.6	1.2	−3.7	3.0
Baseline to mid-treatment	−9.9	5.9	−25.0	−0.1

Note. BMI = body mass index; EI = energy intake; PA = physical activity; MVPA = moderate-to-vigorous physical activity.

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Table 2

Main effect of physical activity (PA) on same-day energy intake (EI)

	b	*SE*	*CI*	*p*
MVPA				
Pre-PA †	60.86	16.00	29.49–92.24	<0.001
Acute post-PA	34.78	13.17	8.95–60.61	0.008
Remaining time in day †	−27.95	20.11	−67.37–11.48	0.165
Full day	−22.89	15.55	−53.39–7.62	0.141
Any-intensity PA				
Pre-PA †	87.76	14.30	59.71–115.80	<0.001
Acute post-PA	25.59	11.26	3.25–47.67	0.023
Remaining time in day †	−5.35	20.29	−45.12–34.43	0.792
Full day	2.08	15.15	−27.62–31.79	0.891

Note. PA = physical activity;

† indicates the model used random intercept only

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Table 3

Relation between energy intake (EI) deviations on physical activity (PA) versus non-PA days and percent weight change

	b	*SE*	*CI*	*p*
EI and weight change across 3-week assessment (MVPA)				
Pre-PA	002	.01	−.024−.028	.91
Acute post-PA	.008	.01	−.016−.032	.50
Remaining time in day	−.010	.01	−.030−.010	.32
Full day	−.001	.01	−.022−.020	.94
EI and weight change across 3-week assessment (Any-intensity PA)				
Pre-PA	.023	.01	−.003−.048	.08
Acute post-PA	−.005	.01	−.028−.019	.68
Remaining time in day	−.002	.01	−.021−.017	.81
Full day	.006	.01	−.011−.023	.50
EI and weight change from baseline to mid-treatment (MVPA)				
Pre-PA	−.001	.05	−.108−.105	.98
Acute post-PA	.003	.05	−.094−.101	.94
Remaining time in day	−.037	.04	−.117−.044	.37
Full day	.020	.04	−.067−.107	.65
EI and weight change from baseline to mid-treatment (Any-intensity PA)				
Pre-PA	.050	.05	−.045−.142	.31
Acute post-PA	.004	.05	−.090−.099	.93
Remaining time in day	.022	.04	−.060−.104	.59
Full day	.030	.04	−.045−.101	.45

Note. EI = energy intake; PA = physical activity; MVPA = moderate-to-vigorous physical activity.