Title: Using pre-prandial blood glucose to assess eating in the absence of hunger in free-living individuals

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Introduction[1]

Research shows that eating in response to hunger facilitates energy homeostasis as an intermediary step in weight regulation (Decastro & Elmore, 1988; Keesey & Powley, 2008; Kissileff & Van Itallie, 1982). In today's permissive food environment, many eating events are unrelated to energy depletion or physiological hunger. Eating in the absence of hunger (**EAH**) is predicted by non-physiological determinants of food intake such as the hedonic properties of palatable foods (Lowe & Butryn, 2007); individual differences in weight-related eating behaviors (S. Schembre, Greene, & Melanson, 2009; S. M. Schembre, 2011); sensitivity to food rewards (Versace, Kypriotakis, Basen-Engquist, & Schembre, 2015; Versace & Schembre, 2015); and impulsivity and self-control (French, Epstein, Jeffery, Blundell, & Wardle, 2012). Prospectively, EAH has been associated with loss-of-control eating, hedonic hunger, and short-term weight gain in women with a BMI < 25 kg/m^2 (Feig, Piers, Kral, & Lowe, 2018). Others have found that perceived EAH may be a relevant target for reducing food intake in individuals with obesity given its high prevalence and association with perceptions of overeating (Goldschmidt, et al., 2017). Consistent with these findings, interventions aimed at self-regulating energy intake, including teaching people to pay more attention to cues of hunger and satiety, are empirically-supported to promote weight-control (Carriere, Khoury, Gunak, & Knauper, 2018; Hintze, Mahmoodianfard, Auguste, & Doucet, 2017). Collectively, this research supports weight control interventions aimed at reducing EAH; however, we lack valid measures to assess EAH among free-living individuals in an effort to determine the efficacy of these interventions on behavioral outcomes or be integrated with ecological momentary assessment (**EMA**) methods to better understand the context in which EAH occurs.

[1] PPBG = pre-prandial blood glucose concentrations; Project TwEATs =Text with Ease Appetite Tracking System; EMA = ecological momentary assessment

To date, EAH has been assessed using questionnaires and laboratory-based paradigms but there are no methods to assess EAH as it occurs in peoples' natural environments. Several self-report surveys have been developed to incorporate various theory-based measures of weight-related eating behaviors including the Three Factor Eating Questionnaire (Stunkard & Messick, 1985), the Dutch Eating Behavior Questionnaire (van Strien, Frijters, Bergers, & Defares, 1986), and the Weight-Related Eating Questionnaire (S. Schembre, et al., 2009). Specifically, these questionnaires assess dietary restraint, disinhibition of dietary restraint (disinhibition), external eating, and emotional eating, which are described as indices of EAH. Self-reported measures of hedonic eating behaviors have been shown to have modest, but sometimes inconsistent (Herman & Polivy, 2008) associations with obesity and weight gain, disordered eating, and central adiposity (S. M. Schembre, 2011; S. M. Schembre, et al., 2012; Wardle, 1987). Inconsistent findings may be, in part, the result of the inherent limitations of self-report questionnaires. People are known to pay little attention to what they eat and research shows that recall biases, including social desirability and body image, influence the accuracy with which diet is self-reported (Maurer, et al., 2006). Similarly, psychosocial factors may hinder the assessment of EAH. Research has shown that disordered eating and environmental cues can challenge the internal appetite control system resulting in the misperception of appetite sensations (Bilman, van Kleef, & van Trijp, 2017; Cadena-Schlam & Lopez-Guimera, 2014). Less biased indicators of EAH are needed in the research community. Alternative measures of EAH have been developed and are widely used in research of children's' eating behaviors and modified for adults (Fay, White, Finlayson, & King, 2015; Feig, et al., 2018; Fisher & Birch, 2002). In a laboratory paradigm, researchers provide meals to study participants to satiate them. Within approximately 30 minutes the participants are presented with an opportunistic taste test followed by ad libitum access to the test foods that would otherwise be thrown away. EAH is quantified as the amount of energy consumed (Kcals) during the taste test and ad libitum access. Like the questionnaires, laboratory-based measures of EAH have been associated with (the risk of) obesity and excessive weight gain in children (Lansigan, Emond, & Gilbert-Diamond, 2015) and overeating and higher BMI in adults (Fay, et al., 2015); however, findings have not always been consistent, particularly in older adolescents and adults (Kelly, et al., 2015). Furthermore, there is questionable ecological validity to laboratory-based eating behavior paradigms. The research community needs new approaches for assessing EAH that are less biased and ecologically valid.

When exploring new approaches to assess EAH, it will be important to consider the metabolic foundation of this behavior. One promising biological indicator of EAH that is relatively easy to assess in free-living individuals is glucose. Historically, glucose uptake and utilization were postulated to play a central role in the control of hunger, satiety, and the regulation of body energy balance as part of the glucostatic theory (Chaput & Tremblay, 2009). While the glucostatic theory and beliefs about pre-prandial (i.e., pre-meal) blood glucose patterns as a predictor of meal initiation have evolved over the past several decades (Woods, 2013), elevated blood glucose concentrations following the absorption of a recent meal unarguably reflect a source of readily-available, short-term energy stores (Stipanuk, 2000). Here, we hypothesize that elevated glucose concentrations prior to an eating event (pre-prandial blood glucose; **PPBG**) indicate EAH. In support of this hypothesis, intervention research using PPBG thresholds measured by glucometers to guide meal initiation in a person’s natural environment has proven to be a feasible and effective weight control strategy (Ciampolini, Lovell-Smith, & Sifone, 2010; Jospe, Brown, Roy, & Taylor, 2015). This research used PPBG to “train” individuals to recognize symptoms of hunger to guide decisions about meal initiation. This self-regulation approach is predicated on the hypothesis that feelings of hunger are indicators of the current energy state and that eating in response to lower PPBG rather than to conditioned signals may improve energy balance and reduce metabolic risk factors (Ciampolini & Bianchi, 2006). Early research established a standardized glucose threshold of 85 mg/dl as an indicator of hunger, which was based on historical data on glucose concentrations prior to food requests in infants and trained adults as well as clinical and preclinical studies on glucose patterns prior to meal initiation (Ciampolini & Bianchi, 2006). A limitation of this approach was that, in some individuals, fasting glucose concentrations were greater than 85 mg/dl. To address this limitation, later research personalized glucose thresholds by averaging two glucose concentrations measured after consecutive overnight fasts (Jospe, et al., 2015). This method of personalizing glucose thresholds was found to be feasible such that study participants achieved their threshold multiple times a day (Jospe, et al., 2015) despite being based on longer, overnight fasts. Collectively, this research preliminarily supports the use of PPBG as a biological indicator of EAH. Yet, additional research is needed to develop this approach and examine its validity as a measure of maladaptive eating.

Valid measures of EAH should be associated with obesity and obesity-related behaviors. Research has shown that individuals with overweight or obesity are prone to weak appetite sensations that promote overeating (Brown, et al., 2014). In fact, discordance between perceived hunger (and satiety) and appetite-related biomarkers has been well-demonstrated in published research (Adam & Westerterp-Plantenga, 2005; Pannacciulli, et al., 2006); consistently suggesting that disturbed perceptions of physiological feedback promote overconsumption. Behaviorally, snacking (defined as eating occasions that occur outside of main meals) is steadily rising in the U.S. and has been linked with higher energy intake and weight gain (Bellisle, 2014; Piernas & Popkin, 2010). As a means to formalize a biobehaviorally-based definition for snacking, Chapelot and colleagues suggested that the crucial difference between meals and snacks is the presence or absence of a physiological triggering stimulus such as a low blood glucose concentrations (Chapelot, Marmonier, Aubert, Gausseres, & Louis-Sylvestre, 2004). Relatedly, measures of EAH should differentiate individuals who are of normal weight from those with overweight or obesity and EAH should be more likely at snacks vs. meals.

As a first step to developing methods for using PPBG as ecologically valid, biological indicator of EAH, the current study aimed to: (1) compare the prevalence of EAH defined by self-report (perceived EAH) vs. PPBG-defined EAH; (2) explore the association between perceived EAH and PPBG by BMI status, (3) determine if snacking was associated with perceived and PPBG-defined EAH; and (4) examine the discordance between perceived and PPBG-defined EAH by BMI status and eating event (snack vs. meal). We hypothesized that: (1) there would be more PPBG-defined EAH vs. perceived EAH; (2) PPBG at a perceived EAH event would be higher among participants with a BMI ≥ 25 kg/m^2 as compared to participants with a BMI < 25 kg/m^2; (3) EAH would occur more often at snacks vs. meals; and (4) discordance rates between perceived and PPBG-defined EAH (i.e., perceiving hunger at PPBG-defined EAH events) would be less likely among participants with a BMI < 25 kg/m^2 than participants with a BMI ≥ 25 kg/m^2,and at snacks vs. meals.

Subjects and Methods

Project TwEATs

We launched Project TwEATs I (Text with Ease Appetite Tracking System) to test the use of EMA to collect hourly records of appetitive states and eating behaviors in a sample of free-living individuals (S. M. Schembre & Yuen, 2011). A new sample of participants was recruited as part of a follow up study (Project TwEATs II) that explored the relationship among perceived psychological (psychosocial stress), physiological states (PPBG), and perceived hunger using similar EMA methods for data collection. For the purposes of the current study we used only perceived hunger, PPBG, and eating event type (meal vs. snack) obtained immediately prior to an eating event. We followed all study procedures in accordance with the ethical standards of the Institutional Review Board.

Participants

We recruited convenience sample of college students 18 to 24 years old. Only those students who reported being healthy, were free from chronic diseases that could affect eating patterns or glucose metabolism (e.g. Celiac disease or diabetes), had no history of a diagnosed eating disorder, were not pregnant or lactating, had an unlimited text messaging plan with their mobile telephone service carrier, and were willing to test their blood glucose concentrations with a commercially available glucometer prior to eating were eligible for the study. Two students who initially met the screening requirements were later found ineligible due to elevated fasting blood glucose concentrations measured with a commercially available glucometer (> 99 mg/dl, repeated in duplicate). Elevated glucose concentrations were presumed to indicate a failed overnight fast or impaired glucose metabolism. We referred these students to University Health Services. All study participants provided informed consent, and the Institutional Review Board approved the study protocols.

Design

Project TwEATs II was a 7-day, free-living observational study of college aged men and women occurring during a 13-week spring semester. At study enrollment, participants completed online questionnaires and provided demographic data. Trained study staff later assessed weight, height, and waist circumference. We used commercially available glucometers to measure fasting blood glucose concentrations after an overnight fast (> 8 hours). Fasting was confirmed by self-report and blood glucose concentrations <100 mg/dl. EMA data were collected from participants in their natural environment.

Participant training

Potential participants met with the study coordinator for a one-time visit for eligibility screening, a review of the study protocols, and signing of informed consent. Data collection instructions were provided to participants at this visit. Instructions included an explanation of when to record eating events, how to classify their eating event (meal vs. snack), and how to rate perceived hunger levels and perceived hunger status. Participants were also trained how to use a glucometer.

EMA data sampling scheme

We used event-contingent sampling to collect EMA data about eating events occurring during a 7-day monitoring period on provided paper and pen logs. An eating event was defined as any occasion when a meal or snack was consumed, including calorie-containing meal-replacement beverage (e.g. shakes/smoothies) (Yannakoulia, Melistas, Solomou, & Yiannakouris, 2007). Consistent with previously published literature, meal or snack consumption occurring >15 minutes apart was considered as distinct events (Berteus Forslund, Torgerson, Sjostrom, & Lindroos, 2005; Yannakoulia, et al., 2007). Participants recorded the date and time of each eating event when it occurred (preferably within 5 minutes). Additionally, they were asked to record the eating event as a meal vs. snack based subjectively on the relative size and timing of the event as well as their perceived hunger using the 10-point hunger rating scale. Perceived hunger status (hungry vs. not hungry) was also reported. Specifically, participants were asked to report whether their hunger rating indicated whether they were, if fact, hungry. Lastly, participants were instructed to measure and record their glucose concentration within 5 minutes prior to each eating event using a OneTouch® UltraMini® Blood Glucose Meter (LifeScan, Inc., Milipitas,CA). Participants were encouraged to record all eating events, even if they skipped a glucose measurement. Glucometers and eating logs were returned (in person) at the end of the study for data retrieval. We verified the accuracy of the glucose measurements recorded on the eating log with the glucometer using the time and date stamp matched to each eating event. In the event, the glucose measurement recorded on the eating log did not match the glucometer reading on that date and time, the reading in the glucometer was used as the glucose concentration for that eating event. No glucometer data were omitted.

Research staff manually entered all data into a working database. An alternate staff member verified or corrected data entries by checking the entered data against the recorded data. All data were verified by this method.

Measures

Eating in the absence of hunger. Perceived EAH was defined by self-reported hunger status at eating events (i.e., hunger status of “No” = eating without hunger vs. hunger status of “Yes” = eating with hunger) in an effort to be consistent with the concept of eating in the absence (vs. presence) of hunger. Perceived pre-prandial hunger ratings were additionally collected using a 10-point hunger rating scale (1 = not hungry at all; 10 = extremely hungry; however, several reviews have been published suggesting that appetite ratings are only modestly associated with energy intake (de Graaf, 1993) and that there is considerable inter-individual variability in subjective ratings of this type (Gibbons, Hopkins, Beaulieu, Oustric, & Blundell, 2019). In this study, hunger ratings associated with a hunger status of ‘Yes’ were greater than those associated with a hunger status of ‘No’ (6.2±1.6 vs. 3.0±1.3), respectively, but demonstrated substantial inter-individual variability (‘Yes’, range = 2-10; ‘No’, range =0-6). We also observed intra-individual variability in hunger ratings associated with perceived hunger status indicated by the use of a single hunger rating to indicate a hunger status of both ‘Yes’ and ‘No’ (range = 2-6). This hindered our ability to use an individuals’ hunger ratings to classify them as hungry (or not hungry) at an eating event as has been done by others (Goldschmidt, et al., 2017). Asking participants to report if they perceived themselves as hungry (or not hungry) at an eating event was operationally feasible and reduced measurement error.

We use PPBG thresholds to define an eating event as occurring the absence of a short-term energy deficit (i.e., EAH). EAH was defined in two ways: 1) as an eating event occurring at a PPBG equal to or greater than 85 mg/dl (Ciampolini, et al., 2010); and 2) as eating event occurring at a PPBG that exceeded one’s own fasting blood glucose concentration defined by the average of two morning fasting glucose concentrations (Jospe, et al., 2015).

Discordance between perceived EAH and PPBG-defined EAH. An eating event was determined to be discordant with PPBG-defined EAH if participants self-reported eating when hungry (i.e., self-reported hunger status = “Yes”). As such, we defined discordance as perceiving hunger (self-reported hunger status = “Yes”) at PPBG-defined EAH events.

Statistical Analysis

We conducted multilevel analyses using SAS (version 9.4) to control for clustering within individuals (i.e., multiple responses from one participant). The between-person effect represents the individual mean deviation from the grand mean, and the within-person effect represents deviation from one's own mean at any given EMA prompt (Curran & Bauer, 2011). The results were analyzed using multilevel logistic regression modeling. First, we examined if there was a difference in PPBG between perceived EAH vs. PPBG-defined EAH events. Then, we tested whether perceived EAH was more likely to occur at snacks vs. meals. Next, we retested these associations using PPBG-defined EAH (standardized and personalized were tested separately). Lastly, we tested whether the discordance between perceived EAH and PPBG-defined EAH was more likely to occur at a snack vs. meal. For all the above models, we entered BMI status as an interaction term and retained only the interactions that were significant. All models were controlled for fasting blood glucose concentrations and participants' gender based on literature describing differences in eating behavior between men and women (Asarian & Geary, 2013).

Results

Participant Characteristics

Table 1 summarizes participant characteristics. We enrolled a total of 45 students in Project TwEATs II. A majority of the participants had a BMI < 25 kg/m^2 (60%), were 18-24 years old (20.7±1.5 years), and were college women (64.4%). The average body mass index was 23.6±4.0 kg/m^2 and the average waist circumference was 78.4±9.8 cm. Approximately 75% of the participants identified themselves as Asian (35.6%) or white (40.0%). By design, fasting blood glucose was within normal limits (70-100 mg/dl) with a mean of 88.3±5.4 mg/dl. PPBG ranged from 48-174 mg/dl with a mean of 94.6±15.1 mg/dl.

Table 1 Participant characteristics (N=41)

Characteristic	% or Mean±SD	Range
Sex (% Male)	35.6%	
Race		
White	39.0%	
Asian	36.6%	
Pacific Islander	4.9%	
Mixed race	19.5%	
Reside on-campus	66.7%	
Underclassmen	68.9%	
Never smokers	90.9%	
BMI status [a]		
BMI < 25 kg/m^2	60.0%	
BMI ≥ 25 kg/m^2	40.0%	
BMI (kg/m^2)	23.6±4.0	17.7-36.3
Waist circumference (cm)	78.4±9.8	60.9-108.6
Age (years)	20.7±1.5	18-24
Fasting blood glucose (mg/dl)	88.3±5.4	76.0-98.5
Pre-prandial blood glucose (mg/dl)	94.6±15.1	48-174

[a] Race-specific BMI cut-offs were applied (Asian: Lean < 22.0 kg/m^2; White, Pacific Islander and Mixed race: Lean <25.0 kg/m^2)

Summary of eating event characteristics

Table 2 is a summary of eating event characteristics by BMI status. During the 7-day monitoring period, 963 eating events were reported (21.9 ± 6.8 eating events/person, range = 10 – 43). Of the 963 eating events, 593 (61.6%) were classified as a meal vs. snack. Participants provided 775 event-matched glucometer readings (16.8 ± 8.1 glucometer readings/person, range = 0 – 33) reflecting a compliance rate of 80.6% for reported eating events. Four participants (10%) did not provide any glucometer readings and were not included in the current analysis resulting in analytical sample of N=41 and 764 hunger status-glucose pairs of data. All other data were retained for the analysis.

Table 2. Summary of eating event characteristics by BMI status

	Eating episodes (N=963)	BMI < 25 kg/m^2 (n=623)	BMI ≥ 25 kg/m^2 (n=340)
Eating event type			
Meal	593	61.6%	61.5%
Snack	322	33.7%	32.9%
Missing	48	4.7%	5.6%
Perceived hunger status			
Hungry = "Yes" (non-EAH)	702	70.8%	76.8%
Hungry = "No" (EAH)	241	27.8%	20.0%
Missing	20	1.4%	3.2%
Standardized PPBG-defined EAH			
PPBG < 85 mg/dl (non-EAH)	178	21.0%	13.8%
PPBG ≥ 85 mg/dl (EAH)(	597	60.8%	64.1%
Missing	188	18.1%	22.1%
Personalized PPBG-defined EAH			
PPBG < personalized average fasting glucose concentration (non-EAH)	281	31.8%	24.4%
PPBG ≥ personalized average fasting glucose concentration (EAH)	494	50.1%	53.5%
Missing	188	18.1%	22.1%
Discordance rates			
Perceived EAH vs. standardized PPBG-defined EAH	441	53.1%	66.9%
Perceived EAH vs. personalized PPBG-defined EAH	362	43.8%	54.5%

Note: EAH = eating in the absence of hunger; discordance was defined as perceiving hunger (self-reported hunger status = "Yes") at PPBG-defined EAH events.

Pre-prandial blood glucose concentrations and eating in the absence of hunger

Significantly fewer EAH events were identified by self-report than by PPBG thresholds. Specifically, of the 963 reported eating events, 241 (25.0%) were characterized as perceived EAH. Comparatively, 597 (62.0%) of eating events were identified as EAH by the standardized PPBG thresholds (p=.028) and 494 (51.3%) events were identified as EAH by the personalized PPBG threshold (p=.047).

Perceived EAH was more likely to occur at a higher PPBG (within-person effect, b = 15.01, SE = 2.34, p <.01). BMI status was a significant moderator of this relationship (p_{int} < .01; **Figure 1**) demonstrating that PPBG needed to be higher for an eating event to be perceived as an EAH event among participants with a BMI ≥ 25 kg/m^2 as compared to participants with a BMI < 25 kg/m^2 (b = -8.75, SE = 2.82, p <.01).

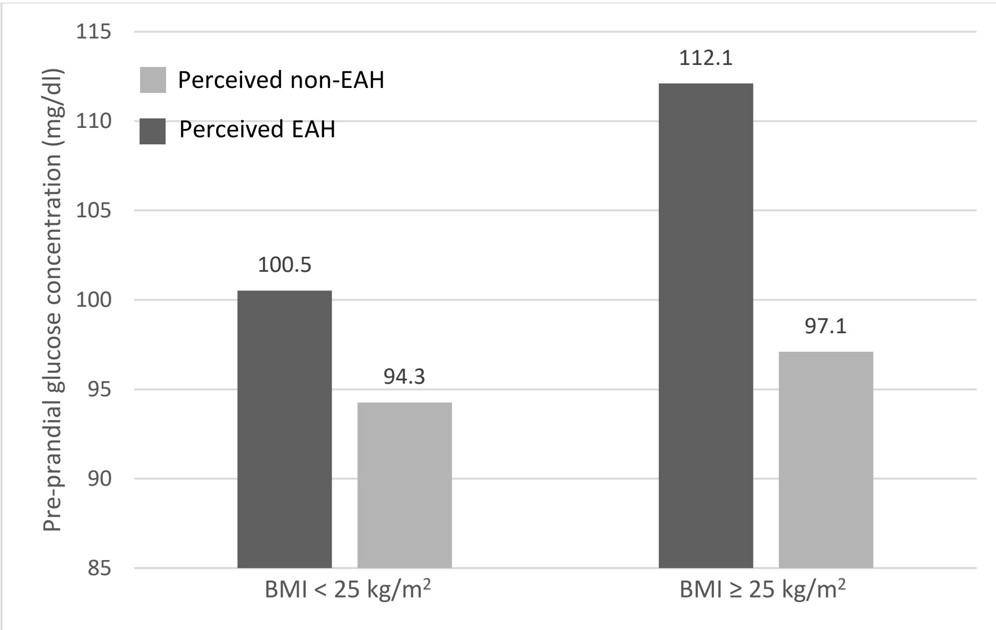

Figure 1. Predicted pre-prandial glucose concentration (mg/dl) by hunger status and BMI status. Note: Reported values are adjusted for sex and fasting blood glucose concentration. EAH = eating in the absence of hunger

Perceived EAH was also more likely to occur at snacks vs. meals (within-person effect; b = 1.54, SE = .21, p = <.01). This was also observed for standardized PPBG-defined EAH (PPBG ≥ 85 mg/dl; within-person effect; b = .56, SE = .21, p < .01) and personalized PPBG-defined EAH (PPBG ≥ fasting BG; within-person effect: b = .40, SE = .17, p = .02).

Discordance between perceived EAH and PPBG-defined EAH

The discordance rate between perceived EAH and standardized PPBG-defined EAH (PPBG > 85 mg/dl) was 57.7%. The discordance rate between the perceived EAH and personalized PPBG-defined EAH (PPBG > average fasting glucose) was 47.4%. Discordance between perceived EAH and PPBG-defined EAH (**Table 2**) was less likely among participants with a BMI < 25 kg/m^2 vs. participants with a BMI ≥ 25 kg/m^2 (standardized PPBG-defined EAH: b = -.88, SE = .31, p < .01 and personalized PPBG-defined EAH: b = -.55, SE = .27, p = .04).

Additionally, there was less discordance between perceived EAH and PPBG-defined EAH at snacks vs. meals (standardized PPBG-defined EAH: within-person effect; $b = -.56$, $SE = .22$, $p = .01$ and personalized PPBG-defined EAH: within-person effect; $b = -.48$, $SE = .19$, $p = .01$).

Discussion

The aims of the current study were to: (1) compare the prevalence of EAH defined by self-report (perceived EAH) vs. PPBG-defined EAH; (2) explore the association between perceived EAH and PPBG by BMI status, (3) determine if snacking was associated with perceived and PPBG-defined EAH; and (4) examine the discordance between perceived and PPBG-defined EAH by BMI status and eating event (snack vs. meal). Our results provide preliminary support for using pre-prandial glucose concentrations as a biological indicator of EAH in free-living individuals. This conclusion is supported by findings that confirmed our hypotheses: (1) PPBG-defined EAH occurred more frequently than perceived EAH; (2) perceived EAH was more likely to occur at a higher PPBG among participants with a BMI ≥ 25 kg/m^2 vs. a BMI < 25 kg/m^2; (3) snacks vs. meals were more likely to be defined as EAH events and; (4) discordance between perceived EAH and PPBG-defined EAH (i.e., perceiving hunger at PPBG-defined EAH events) was less likely among participants with a BMI < 25 kg/m^2 vs. a BMI ≥ 25 kg/m^2 and at snacks vs. meals. We additionally found that the feasibility of using point-of-care glucometers may need further consideration. Here, study recruitment was targeted at those who were willing to use a glucometer before meals and snacks. We had less-than-adequate testing rates (compliance = 80%) and 4 (10%) enrolled participants did not contribute blood glucose data. Despite this limitation, our study shows that PPBG is a good biological indicator of EAH. Our findings warrant further development and testing of this approach in more diverse populations, using less invasive measures of PPBG (i.e., continuous glucose monitoring systems).

Our findings, which demonstrate the preliminary validity of using PPBG to define EAH events, are consistent with previously published research. In a recent review by Simmons and colleagues (Simmons & DeVille, 2017), the authors state that anomalies in the biological pathways through which the body's energy state is communicated to the brain can lead to an inability to accurately detect and respond to signals of energy surplus and satiety, promoting non-homeostatic feeding, prolonged positive energy balance, and obesity. They further conclude that obesity may be associated with hypersensitivity to interoceptive signals of hunger. Consistent with this model of obesity, we found that individuals with a BMI ≥ 25 kg/m^2 perceived themselves as hungry at a higher PPBG and were more likely to perceive themselves as hungry at a PPBG-defined EAH event as compared to individuals with a BMI < 25 kg/m^2. Also, our finding that discordance rates between perceived EAH and PPBG-defined EAH were lower at snacks vs. meals is consistent with prior research on opportunistic snacking behavior. In lab-based measures of EAH, participants consume a provided meal until reportedly full before initiating a taste test of snack foods. The quantity (Kcals) of snack foods consumed is used as the measure of EAH. In this paradigm, adult participants provide appetite ratings that confirm an absence of hunger prior to the taste test suggesting their perceived hunger is concordant with their physiological hunger (Feig, et al., 2018). Rather than a misperception of physiological hunger, psychological factors such as sensitivity to food rewards, impulsivity, and BMI have been associated with snacking in the absence of hunger in lab-based studies (Fay, et al., 2015). Similarly, other non-lab-based studies have reported that food craving is a stronger predictor of snacking than reported hunger (Cleobury & Tapper, 2014; Richard, Meule, Reichenberger, & Blechert, 2017). This literature further supports our findings that PPBG can be used as a biological indicator of EAH among free-living individuals.

Our study is further strengthened by collecting data from participants in their natural environments. This led to a large sample of eating events and PPBG pairs. To our knowledge this is the first study to collect repeated days of perceived appetite and physiological data. Here, we have more than 750 pairs of data. The benefit of collecting these data in peoples' natural environments is that compared to data collected in a laboratory, our data has a high level of ecological validity. Despite these important strengths, there are notable limitations that will need to be addressed in similar future research. First, we recruited a generally homogeneous convenience sample of young adults with fasting blood glucose concentrations within normal limits. Participants were attending college and may have eating patterns that differ from the general population due to variability in their schedules from day to day and access to food. While this approach suited the purpose of the current study, it will be important to replicate these findings in larger more diverse samples with individuals with and without impaired glucose metabolism. Second, we purposefully recruited participants who agreed to use a commercially available glucometer prior to all meals and snacks. This introduces an important sampling bias when considering the collection of glucose data in the future. Relatedly, in this sample, we found modest compliance rates (80%) with the request to test PPBG prior to reported meals and snacks. As such, nearly 20% of the reported eating events were not included in our analyses due to missing PPBG measurements. Despite these missing data, our conclusions remain based on a substantial number event-matched glucometer readings (N=775; 19 of 23 reported eating events per person). We also observed that 4 (10%) participants provided no PPBG data at all. These compliance rates were lower than what has been previously published intervention studies with similar testing protocols (Ciampolini & Bianchi, 2006; Jospe, et al., 2015) suggesting that participants may need added motivation to improve compliance rates with point-of-care glucometers. Also, this study lacked a ground truth observation of the time eating events occurred. This resulted in having to assume the accuracy of the time participants took pre-prandial glucometer readings. As such, it is possible that glucometer readings were taken outside of the requested 5 minute window prior to an eating event. These data suggest that alternative methods of collecting blood glucose data should be considered in future research and that it is important to have a ground truth observation of time when eating events occur. A less invasive approach that would also provide additional data on blood glucose dynamics before and after food intake would be continuous glucose monitoring.

Conclusions

The findings of this study were consistent with our hypotheses and, therefore, support the continued refinement and validation of methods to assess EAH using PPBG in larger and more diverse samples of free-living individuals. Hypotheses regarding the use of PPBG for this purpose were supported by previous literature showing that weak appetite sensations promote obesity and obesity-related behaviors and by clinical research showing that eating when glucose concentrations are low (defined by standardized and personalized thresholds) is a feasible and effective self-regulation strategy that promotes weight control (Ciampolini, et al., 2010; Jospe, et al., 2015). As such, researchers may choose to integrate these methods with the collection of contextual data using the same EMA-based data collection platform in an effort to better understand and intervene on EAH in real-time using just-in-time adaptive interventions (JITAI). Also, future weight control studies aimed at promoting the self-regulation of energy intake might explore using these assessment methods to determine the effect of the intervention on EAH.

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Contributors

SMS and SK designed the research; SMS conducted the research; SMS, YL, and JL analyzed the data; SMS, YL, JH, and SK were involved in manuscript preparation; SMS had primary responsibility for the final content.

Conflict of Interest

The authors do not have any financial or personal relationships to disclose.

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