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Smartphones for smarter eating:

Elucidating eating behaviors, stress, and heart rate variability

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in
Clinical Psychology
by
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The dissertation of Kathryn M. Godfrey is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

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FIELDS OF STUDY

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ABSTRACT OF THE DISSERTATION

Smartphones for smarter eating:
Elucidating eating behaviors, stress, and heart rate variability

by

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Doctor of Philosophy in Clinical Psychology

University of California, San Diego, 2017

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Rationale: Binge eating puts individuals at risk for dropout of weight loss treatments and weight regain after treatment. However, treatments for binge eating have not been successful at influencing weight. To improve obesity treatment, research needs to examine binge eating with new theoretical approaches, interdisciplinary paradigms that span physiological, psychological, and behavioral bases, and designs that enable study of eating behaviors within real world settings. The current study examined stress and binge eating, with a design that integrated ecological momentary assessment (EMA) of stress and binge eating behavior with psychophysiological monitoring of the autonomic nervous system (ANS). The ANS is crucial for self-regulation, especially responding to and recovering from stressors. ANS flexibility captures the body's ability to dynamically balance the sympathetic and parasympathetic nervous systems, and low ANS flexibility is related to numerous psychological and physical health stressors. Measures of heart rate variability (HRV) are indicators of ANS flexibility and can be obtained through non-invasive, ambulatory methods. The specific aims were to: 1) examine if lab-based HRV at baseline and when stressed by an experimental protocol is related to binge eating behaviors recalled from the previous four weeks and during a seven day at-home data collection period; 2) analyze if self-reported stress precedes binge eating during a seven day at-home data collection period; and 3) describe the experience of wearing a portable HR monitor and using a smartphone with EMA and the feasibility for clinical use in assessment and intervention.

Design: 32 male and female participants with obesity completed a single lab visit to measure HRV and assess binge eating in the previous four weeks. HRV was measured through a lab protocol containing 5 minute recordings during a baseline period and a mental stressor. A subsample (*n*=16) of participants also completed a seven day at-home protocol for EMA assessment of stress and binge eating using a smartphone. During the seven days, participants self-reported stress using the 4-item version of the Cohen Perceived Stress Scale before each eating episode and reported their eating behaviors after they finished eating. Participants wore a HR monitor for one day of the seven days of the at-home protocol. At the end of the at-home protocol, these 16 participants underwent a semi-structured interviews and completed self-report questionnaires assessing their experience in the study and exploring the potential feasibility and clinical utility of systems using the study devices. Multiple linear regression, longitudinal multilevel mixed effects models, and qualitative, thematic content analysis were performed.

Results: The sample was comprised of mostly female, non-Hispanic/Latino white or African American single participants, with either some college or a Bachelor's degree and a range of household incomes. At the first lab visit, many HRV measures (RMSSD, HF, LFn, HFn, LF/HF ratio) were significantly different between the baseline and stressed conditions ($p = 0.01$ to $p < 0.001$). Significant relationships were found between HRV variables at baseline and both loss of control (SDNN $B = -1.26$, $p = 0.03$, lnHF $B = -0.06$, $p = 0.04$) and overeating (LFn $B = 0.01$, $p = 0.04$) from the previous four weeks. No significant associations were found for HRV variables under stress, nor among HRV and binge eating behaviors from the at-home portion. Analyses of the at-home EMA data revealed that higher self-reported stress was linked to increased probability of overeating and loss of control overeating ($p = 0.011$ to $p < 0.001$) but not of eating non-nutritious, high calorie foods, or breaking dietary rules. Results from adherence data, self-report questionnaires, and semi-structured interview suggest that participants were adherent to study procedures and found them to be straightforward. Participants expressed enthusiasm for elements of the study and for clinical applications of the study system and provided numerous suggestions for improvement.

Conclusions: Findings confirm the link between stress and binge eating behaviors in obesity and provide insights for future research and clinical applications. Measures of

ANS flexibility in the lab and increased self-reported stress during the at-home EMA portion were associated with more severe binge eating behaviors. Continuing this line of could inform the development of technologies that detect stress and provide just-in-time adaptive interventions when individuals are at risk for binge eating, improving the capacities and reach of evidence-based interventions for binge eating and weight management.

Introduction

Obesity

Obesity (Body Mass Index [BMI] $\geq$ 30 kg/m^2) and overweight (25 kg/m^2 $\leq$ BMI $\geq$ 30 kg/m^2) are significant public health concerns in the United States today (US Department of Health Human Services, 2004). An alarming two-thirds of Americans are obese or overweight (Ogden, Carroll, Kit, & Flegal, 2014). Recent projections predict that by 2030 the US will have 65 million more individuals with obesity (Wang, McPherson, Marsh, Gortmaker, & Brown, 2011). The increasing prevalence of obesity and overweight is especially concerning given the numerous physical health (Must et al., 1999), economic (Lehnert, Sonntag, Konnopka, Riedel-Heller, & Konig, 2013), occupational (Cawley, Rizzo, & Haas, 2007), and psychological (Mather, Cox, Enns, & Sareen, 2009) costs of these conditions on individuals and society. Given the high rates of obesity and overweight and the substantial costs of the conditions and their associated problems even relatively small reductions or plateaus of BMI across the population could result is significantly reduced burden of disease and increased quality of life (Wang et al., 2011).

Obesity treatments and long term weight management

Lifestyle treatments for obesity seek to reduce weight by increasing energy expenditure through physical activity and decrease energy intake through diet. There has been an increasing interest in adding surgical and pharmaceutical treatments in addition to healthy lifestyle modifications for weight loss. Surgical treatments involve either gastric restriction or altering nutrient absorption whereas pharmaceutical treatments may alter appetite or food intake, change metabolism, or increase energy expenditure (DeWald, Khaodhiar, Donahue, & Blackburn, 2006). These interventions demonstrate good weight loss outcomes in the short term, but individuals who choose surgical or pharmaceutical interventions may experience significant side effects that may decrease treatment utilization (DeWald et al., 2006), and an overwhelming majority of individuals will regain weight (DeWald et al., 2006; Wing & Phelan, 2005). Overall, this evidence suggests that current treatments are not successfully targeting one or several key and long-term determinants of poor weight management. There are significant barriers to translating short term weight loss strategies and interventions into skills for successfully maintaining a healthy weight in the long term.

According to the ecological model obesity is more than an imbalance of energy in to energy out (Egger & Swinburn, 1997). Rather, obesity is greatly impacted by biological, environmental, and behavioral factors that together contribute to energy balance and to how individuals respond to changes in weight, for example from weight loss. Genes influence individuals' predisposition to obesity, the ability to create fat cells, and the obesity-related hormone and metabolic functions (Yang, Kelly, & He, 2007). However, the impact of genes on obesity may reduce throughout the lifespan thus increasing the importance of behavior and the environment on weight (Hewitt, 1997). Researchers are examining the role of childhood and built environments in determining weight (Crossman, Anne Sullivan, & Benin, 2006; Mackenbach et al., 2014; Vamosi, Heitmann, & Kyvik, 2010), but there is no consensus about which risk factors are most important and concern that intervening on these factors may not result in long term weight loss or reductions in obesity (Ferdinand, Sen, Rahurkar, Engler, &

Menachemi, 2012; Sallis & Glanz, 2006; Stuart, Broome, Smith, & Weaver, 2005). Social environments could play a role in weight-related health behaviors and decision making (Christakis & Fowler, 2007; Salvy, Jarrin, Paluch, Irfan, & Pliner, 2007). Psychological and behavioral factors contribute to the development and maintenance of obesity. For example, emotion regulation and how individuals respond to stress have been implicated in unhealthy eating behaviors, such as binge eating (Dallman, 2010; Oliver, Wardle, & Gibson, 2000). Of all the factors that influence obesity and long term weight management the psychological and behavioral determinants may prove the best target for intervention as modifying them would require fewer expensive macro-level or system-wide changes. Further, the widespread use of technology like smartphones to support lifestyle changes may enable personalized, mobile assessment of psychological constructs and health behaviors and allow for real-time and long term treatment.

Psychology and eating behaviors

Behavior and lifestyle change for long term weight management may require a more complex understanding of weight loss and maintenance behaviors beyond the simplistic message of eating less and exercising more (Elfhag & Rossner, 2005; Wing & Hill, 2001). Failing to take into account the influence of psychological factors on eating behaviors may decrease the interest in or actually reverse effects of a lifestyle intervention for weight loss. For example, 82% of Americans report that one reason they do not eat healthier is that they do not want to give up foods they like to eat (Academy of Nutrition and Dietetics, 2011), and the tendency for dichotomous, all-or-nothing thinking is a strong predictor of weight regain (Byrne, Cooper, & Fairburn, 2004). Continued study and treatment of these and other psychological influences on eating behaviors and healthy weight management has the potential to encourage weight loss and reduce obesity.

Psychological stress from the perception of demands exceeding coping resources or from negative affect has been examined as a determinant of unhealthy eating behaviors with mixed findings overall. Lab studies in both humans and animals have found that inducing acute stressors can result in either decreased or increased food consumption (Greeno & Wing, 1994; Torres & Nowson, 2007). Research on stress and eating has also supported that highly palatable and caloric foods are more likely to be overeaten during periods of stress in both humans and rats (Boggiano et al., 2007; Torres & Nowson, 2007). However, the consumption of highly palatable foods after stress may be unique to individuals with emotional eating or those who tend to eat in response to emotions (Oliver et al., 2000). Therefore the type of food eaten and the tendency to eat in response to emotions are other important factors to consider when examining the stress-eating relationship, increasing the complexity of requirements and recommendations for healthy weight management.

Stress and strong emotions are major psychological contributors to unhealthy eating behaviors such as binge eating, which exacerbates poor weight management in individuals with obesity. Binge eating is defined as overeating while experiencing loss of control (American Psychiatric Association, 2013; Vannucci et al., 2013), and episodes of binge eating are associated with numerous emotional features such as depression, self-disgust, guilt, and embarrassment. Negative affect and stress are common triggers for binge eating episodes (Arnow, Kenardy, & Agras, 1992; Haedt-Matt & Keel, 2011b). Binge eating is a risk factor for drop out of weight loss treatments and for weight regain in individuals who have achieved weight loss (Elfhag & Rossner, 2005; McGuire, Wing, Klem, Lang, & Hill, 1999; Teixeira et al., 2004). Binge eating behavior and loss of control over eating contribute to weight regain and poor weight management of individuals who have undergone bariatric surgery (Meany, Conceicao, & Mitchell, 2014).

In the United States 2.6% of the general population and 23-46% of individuals in weight control programs will meet criteria for Binge Eating Disorder (BED) during their lifetime, a diagnosis which is associated with higher BMI and increased risk of obesity (de Zwaan & Mitchell, 1992; Kessler et al., 2013; Spitzer et al., 1993). This prevalence estimate may grow as more population-based studies are done with the Diagnostic and Statistical Manual-5 (DSM-5) BED criteria, which requires fewer weekly binge episodes to meet diagnostic criteria (American Psychiatric Association, 2013). BED is related to obesity and weight fluctuations, and the prevalence of BED increases in groups with higher BMI (Dingemans, Bruna, & Van Furth, 2002). Individuals with BED have significantly lower quality of life and social functioning, more pain, increased BMI, and higher prevalence of psychiatric co-morbidities compared to individuals with obesity who do not binge eat, which suggests that binge eating behavior presents problems above and beyond those from obesity alone (Rieger, Wilfley, Stein, Marino, & Crow, 2005; Vancampfort et al., 2014; Wilfley, Wilson, & Agras, 2003; Winkler et al., 2014). BED exacerbates the burden of other obesity-related conditions as individuals with both BED and type II diabetes have higher weight gain and insulin resistance (Munsch & Herpertz, 2011). BED has been shown to precede the onset of type II diabetes (Herpertz et al., 1998), highlighting the role of binge eating behavior in the development of obesity and associated health conditions.

Stress is associated with binge eating behavior even in individuals that do not meet criteria for BED (Sulkowski, Dempsey, & Dempsey, 2011). Binge eating behavior in populations with obesity may lie on a continuum as research examining dieting, weight history, body image, negative affect, and self-esteem in BED and in sub-threshold BED found that these two groups do not significantly differ along many of these variables (Striegel-Moore, Wilson, Wilfley, Elder, & Brownell, 1998). Binge eating behavior is also problematic within bulimia nervosa, which is another diagnosis associated with obesity so it is crucial to study and treat binge eating behavior not only in BED populations but also in individuals with obesity who engage in binge eating behavior (Marcus & Wildes, 2014). In addition to overeating and loss of control over eating, binge eating behavior often includes consumption of non-nutritious, high calorie foods such as burgers, candy, and pastries, which are also foods commonly consumed during stress-related eating (Arikian et al., 2012; Groesz et al., 2012). Binge eating behavior has also been associated with breaking dietary rules such as set portions or a calorie limit in a phenomenon similar to the abstinence violation effect of substance use (Arnow et al., 1992). Overall, it is of both scientific and public health significance to examine binge eating behavior in individuals with obesity regardless of BED or other diagnostic status.

Despite having effective treatments for binge eating (Wilson, Wilfley, Agras, & Bryson, 2010), the connections between these unhealthy eating behaviors and weight management are not well understood because interventions targeting specific eating behaviors have shown only mixed results influencing weight (Munsch et al., 2007; Wonderlich, de Zwaan, Mitchell, Peterson, & Crow, 2003; Yanovski, 2003). Questions remain about how treatment-induced changes in binge eating affect weight, obesity-related health conditions, and health functioning (Heaner & Walsh, 2013). Given the prevalence and associated health concerns of binge eating behavior and BED, the relationship between stress and binge eating, and the limited efficacy of treatment on weight, binge eating and the psychological correlates need to be further explored as intervention targets to improve healthy weight management in individuals with obesity.

Models of binge eating

Theoretical models of binge eating emphasize that binge eating behaviors serve as a coping response to reduce negative emotions. The Psychosomatic Theory of obesity suggests that individuals with obesity eat in response to uncomfortable emotional states (Canetti, Bachar, & Berry, 2002; Kaplan & Kaplan, 1957).The Emotion-Regulation Model (ERM) suggests that binge eating is triggered by negative emotions and provides relief or distraction from them (Hawkins & Clement, 1984). The validity of these emotion regulation models has been examined using ecological momentary assessment (EMA). Findings indicate binge eating is often a coping response to negative emotions, but people who overeat in response to emotions do not feel relief after eating (Haedt-Matt & Keel, 2011b). Therefore, the premise that binge eating regulates emotions may be insufficient and limits the impact interventions based on these theories can have on weight management.

The proposed project challenges the ERM for binge eating, an insufficient paradigm for solving poor weight management in individuals with obesity. The

Reflective Impulsive Model (RIM) whereby the balance between two systems (reflective versus impulsive) guides health-related choices, may provide a better description of the relationship between stress and eating (Hofmann, Friese, & Wiers, 2008). Figure 1 depicts the RIM for unhealthy eating behaviors, such as binge eating. The reflective system is comprised of reasoned attitudes and restraint standards necessary in planning, goal setting, judgments, and decision making for eating behaviors. The impulsive system has automatic affective and approach-avoidance reactions related to habitual or instinctive responses. When stress levels are below threshold the reflective system keeps the impulsive system in check (Figure 1A). However when stress surpasses the threshold, the reflective system is less able to counteract the impulsive system thus making the individual more susceptible to engaging in behaviors like overeating (Figure 1B). Therefore, under less stressed circumstances individuals trying to lose weight or maintain weight loss may be able to adhere to dietary guidelines such as limited caloric intake. However, as stress increases and the individual's threshold is crossed the reflective system is less able to counteract the impulsive system thus making the individual more susceptible to engaging in unhealthy eating behaviors. The potential for intervention using the RIM is in the ability to detect the individual's threshold level of stress and the moment at which the stress threshold is surpassed such that the impulsive system is more heavily influencing eating behaviors.

The RIM is consistent with the strength model of self-control (Baumeister, Vohs, & Tice, 2007; Hagger, Wood, Stiff, & Chatzisarantis, 2010), self-regulation resources (Vohs & Heatherton, 2000), and the disinhibition effect of dietary restraint theory (DRT) (Herman & Mack, 1975) as these theories all contain higher-order processes that inhibit habitual or instinctive responses until depleted or under stress. The RIM for binge eating is also in line with newly burgeoning research linking neural circuits involved in self-regulation and impulse control with binge eating (Marcus & Wildes, 2014). Unlike DRT, RIM for binge eating in individuals with obesity considers any conscious attempts to influence eating behaviors either towards or away from choices in the moment rather than emphasizing a stable trait of dietary restraint focused only on the avoiding, cutting back on, or restricting of eating. For example, under DRT an individual who is trying to lose weight by choosing healthier foods (e.g., an apple versus a cookie) may not be seen as exerting restraint whereas under the RIM this choice still requires using the reflective system to override the habitual or potentially more satisfying choice of a cookie. Notably, there has been debate about the disinhibition effect of DRT with calls for more studies to be conducted in real world, non-lab settings to examine how triggers such as stress and non-stressful cognitive load influence the balance between dietary restraint and overeating (Lowe & Kral, 2006; Ouwens, van Strien, & van der Staak, 2003; Westenhoefer, Broeckmann, Münch, & Pudel, 1994). Findings from the RIM for binge eating will likely allow for parallels to the restraint model and further inform development of theoretical models of the relationship between stress and binge eating behaviors.

Ecological momentary assessment

The ineffectiveness of binge eating treatments on weight management may be due to the limited understanding of how stress influences eating behavior, especially relying on results from lab-based research. On the one hand, individuals who binge eat often self-report the occurrence of overeating in response to negative emotions as a way to compensate or cope (Ganley, 1989). On the other hand, experimentally induced negative affect has not been associated with increased caloric consumption or binge eating in a lab setting (Stice, 2002). The inconsistent findings may reflect the recall bias of retrospective self-report or limited ecological validity of experimental research paradigms. In ambulatory or naturalistic research techniques using EMA participants complete self-report measures at several points during their day to capture how they are feeling and behaving in the moment (Shiffman, Stone, & Hufford, 2008; Yoshiuchi, Yamamoto, & Akabayashi, 2008). Naturalistic study of binge eating has been proposed as a needed method of assessment to objectively and accurately understand eating behaviors (Walsh, 2011). EMA methods have been used to evaluate the link between emotions and eating behaviors in both clinical and non-clinical samples (Macht & Simons, 2000; Stein et al., 2007). Examining the interplay of stress and binge eating using EMA may help overcome the methodological shortcomings of lab-based paradigms and provide increased ecological validity.

Mobile physiological assessment and intervention of eating behaviors

The autonomic nervous system (ANS) is crucial for self-regulation, especially responding to and recovering from stressors (Thayer & Sternberg, 2006). ANS flexibility captures the body's ability to dynamically balance the sympathetic and parasympathetic nervous systems, and low ANS flexibility is related to numerous psychological and physical health stressors (Thayer & Sternberg, 2006). Research on the impact of stress and negative emotions support the role of low ANS flexibility, especially withdrawal of parasympathetic activity, on poor mental and physical health through complex networks of stress response, immune, and other physiological systems (Thayer & Sternberg, 2006). Assessment of ANS flexibility can augment traditional self-report measures of stress providing more objective measures of the stress response and individual differences in emotion regulation (Appelhans & Luecken, 2006; Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012). Stress and eating research has examined if objective measures of physiological stress that capture ANS flexibility through cortisol, blood pressure, and heart rate (HR) are related to cravings, hunger, and eating behavior with cross sectional (Groesz et al., 2012) and experimental stress (Epel, Lapidus, McEwen, & Brownell, 2001; Gluck, Geliebter, Hung, & Yahav, 2004; Rutledge & Linden, 1998).

Heart rate variability (HRV) is one commonly used measure of ANS flexibility that appeals to researchers because it can be derived from data collected by relatively non-invasive HR monitors, which also have the potential for mobile psychophysiological assessment. HRV can be measured both time and frequency domains. Time domain measures are calculated by examining the segments between heartbeats or normal-to-normal (NN) intervals measured in milliseconds (ms). Mathematical manipulations of the NN variable produce numerous HRV variables such as the standard deviation of NN intervals (SDNN) and root mean square of successive differences between NN intervals (RMSSD). Frequency domain components of HRV include power in the very low frequency range (VLF; ≤ 0.04 Hz), low frequency range (LF; 0.04-0.15 Hz), and high frequency range (HF; 0.15-0.4 Hz) measured in ms^2. Mathematical manipulations of these frequency domain measures, such as the LF/HR ratio, are also used. Low frequency norm (LFn) and high frequency norm (HFn) values minimize the effect of changes in the VLF and may be more suitable than the LF and HF values for comparisons across a range of subjects (VivoSense, 2012). HRV recordings of short durations (e.g., 5 minutes) are best interpreted with frequency domain measures, but SDNN and RMSSD are acceptable time domain measures for shorter recordings (Task Force of The European Society of Cardiology and the North American Society for Pacing and Electrophysiology, 1996). Models of HRV have related frequency domain measures to specific ANS components (HF power measures parasympathetic tone; LF power measures sympathetic tone; LF/HF ratio measures the sympathovagal balance), but newer theory has questioned these interpretations and supported that HF power and LF power correspond to parasympathetic activity and suggested cautious interpretation of the LF/HF ratio due to continued debate among experts on what it captures (Reyes del Paso, Langewitz, Mulder, van Roon, & Duschek, 2013; Shaffer, McCraty, & Zerr, 2014). Unlike frequency domain HRV measures, the time domain measures do not allow for interpretation of corresponding ANS systems (Shaffer et al., 2014).

There are very few studies of HRV and binge eating, and those that exist show inconsistent results. Individuals with BED have stable HF power during a stressor (Stroop color/word interference task) and recovery whereas individuals with obesity who do not binge eat had HF power reduction during stress and increase in HF power during recovery from the stressor (Messerli-Burgy, Engesser, Lemmenmeier, Steptoe, & Laederach-Hofmann, 2010). A similar study found conflicting results as individuals with BED had greater reduction in HF power from baseline to stressed conditions (Stroop and a delayed auditory task) compared to individuals with obesity who do not binge eat, and a greater reduction in HF power from baseline to stressed was associated with more self-reported binge eating episodes (Friederich et al., 2006). Another study reported differences in HF power or LF/HF ratio variables between individuals with BED and healthy controls while listening to a script of a recent stressful event and in recovery conditions, and no significant correlations were found between HF power, LF power, or LF/HF ratio and binge eating episodes (Hilbert, Vogele, Tuschen-Caffier, & Hartmann, 2011). Hilbert and colleagues' (2011) lack of significant findings may be due to the stressor used, which participants reported induced psychological but not physiological stress. Baseline differences in HRV variables between BED and non-BED groups have not been observed (Friederich et al., 2006; Hilbert et al., 2011; Messerli-Burgy et al., 2010). ANS flexibility measured with and without induced stressors may be essential to studying who is at risk for binge eating behaviors. Research on the association between HRV and binge eating has not produced consistent results, and more studies are needed to further examine this association.

Psychophysiological monitoring of ANS flexibility can also be used to design alerting systems for mobile assessment and intervention. Under the RIM, successful intervention of binge eating triggered by stress requires detecting when the impulsive system is driving behaviors by assessing stress states (Figure 1). Ambulatory monitoring of ANS flexibility and HRV is available using Holter monitors, which can be expensive and require participants to affix electrode stickers to their abdomen. The technological advances in mobile psychophysiological instruments provides promise of more comfortable, convenient, and cost-effective real-time stress monitoring using chest straps or wrist worn devices. As psychophysiological assessment methods improve in hardware and data quality they can be merged with EMA methods to provide a continuous, objective measures of emotional states (Wilhelm, Pfaltz, & Grossman, 2006). Awareness of increased stress, impaired decision-making ability, and susceptibility to unhealthy eating could enable individualized just-in-time adaptive intervention in individuals with obesity who engage in binge eating. No published study to date has incorporated physiological monitoring of ANS flexibility with an EMA design. This innovative research would form the essential foundations for building smartphone systems that use psychophysiological measures to trigger just-in-time adaptive interventions for eating behaviors.

Mobile technologies and smartphones are also promising tools for assessing eating behaviors and dietary intake. Using a smartphone camera to take photos and report eating behaviors may increase accuracy of self-reported food intake by reducing retrospective recall bias and reduce the burden of reporting each food item eaten if individuals can take photos of food (Ngo et al., 2009; Sharp & Allman-Farinelli, 2014). Individuals prefer monitoring their diet using mobile technologies over conventional methods, but there has not been significant evidence that these methods increase accuracy possibility due to missed assessments, poor photo quality, and limited dietary and portion information (Sharp & Allman-Farinelli, 2014). Assessing diet content and eating behavior is remarkably complex and presents a barrier to use of mobile technologies within weight management populations. Reporting dietary intake using smartphone apps can be challenging even with extensive food databases or scanners to document food products (Tang, Abraham, Stamp, & Greaves, 2015). This area of research is still in its infancy, and more work is needed to validate smartphone-based methods of assessing dietary content and eating behaviors and determine the feasibility and practicality within clinical populations.

Capitalizing on these technologies to better understand and intervene on binge eating behaviors, several engineering groups have created systems to study the stress-eating relationship (Carroll et al., 2013; Tam, 2011). Despite successful development of such systems, they have not been scientifically studied with the clinical populations whose struggle with weight loss provided the initial rationale for their design. Taking these systems from concept to actually helping individuals with obesity requires studying the relationship between stress and eating in this population, understanding their experiences, and examining the clinical feasibility of the technology. More research examining wearable psychophysiological tools in clinical samples is needed before mobile systems for assessment and intervention of stress-related unhealthy eating can be used clinically for weight management. A naturalistic study has not yet integrated eating behaviors, stress, and ANS functioning to elucidate the role stress plays in binge eating behaviors (Stice, 2002), the findings from which could inform the nature of this association and inform real-time intervention.

Summary and limitations of prior research

Although obesity and overweight have been recognized as significant public health problems, treatments have not yet demonstrated long term efficacy and have been insufficient to tackle the challenges of these conditions and their associated problems. Stress-related eating behaviors, such as binge eating, are risk factors for poor weight management and reduced effectiveness of weight loss treatments and are therefore potential targets for treatment. However interventions for binge eating do not appear to influence weight, which indicates a failure to fully understand the true nature of the stress-binge eating relationship. New approaches to treat unhealthy eating have emerged with a focus on studying eating in naturalistic settings and integrating physiological, psychological, and behavioral assessment. Significant gaps and inconclusive findings remain in the disparate body of literature, and more research is needed to improve theoretical models, to better understand the relationship between stress and eating, and to inform the development of technology-enhanced treatments that demonstrate long term maintenance of healthy weight within clinical populations.

Aims

This study examined the relationship between stress and binge eating in lab and naturalistic settings. The design integrated EMA of stress and eating behavior with psychophysiological monitoring of stress in the lab. The objectives of this project were to study the associations among stress, binge eating, and ANS flexibility in individuals with obesity who binge eat and to examine the potential of an innovative psychophysiological assessment for future use in treatment. This investigation analyzed how ANS flexibility and stressful conditions relate to binge eating to inform future development of individualized, real-time intervention in a naturalistic setting through building awareness of momentary stress and impaired decision-making. With an improved theoretical model, advanced mobile technologies, and a clinically-relevant population, the study examined the stress and binge eating relationship and assessed the feasibility of naturalistic psychophysiological assessment in individuals with obesity, ultimately building the foundation for novel, innovative research in stress and eating. The new insights afforded by this project are of pressing importance as we continue to develop and refine innovative interventions targeting obesity, one of the most substantial public health concerns today.

Specific aims and hypotheses are:

Aim 1: Examine if frequency of binge eating behaviors during the four weeks before the first lab visit and during the at-home protocol were related to HRV variables at baseline and when stressed (by an experimental protocol). *This aim investigated the relationship between HRV and binge eating behaviors.* Hypothesis: higher frequency of self-reported binge eating behaviors will be associated with lower HRV at baseline and when stressed.

Aim 2: Analyze if self-reported stress precedes binge eating during a seven day at-home data collection period. *This aim replicated previous findings and examined the potential to use more advanced methodology to photo-validate self-reported binge eating behaviors.* Hypothesis: Higher self-reported stress will be associated with an increased chance of engaging in binge eating behaviors.

Aim 3: Describe the experience of wearing a portable HR monitor and using a smartphone with EMA and the feasibility for clinical use in assessment and intervention. *This aim explored if future EMA studies using HRV or other psychophysiological measures as triggers for assessment or intervention are feasible and provided recommendations for future research.* Hypothesis: none

Methods

Overview of study

Potential participants were screened over the phone for inclusion and exclusion criteria. Based on this screening, eligible participants were enrolled into the study and attended the first lab visit where they provided informed consent. All participants (*N* = 32) completed the first lab visit, and a subsample of participants (*n* = 16) continued in the study to complete 7 at-home days followed by the second lab visit. Table 1 displays study visits, measures administered, and other procedures in the overall study protocol. The first lab visit involved a) obtaining consent; b) performing an anthropometric assessment; c) assessing binge eating behaviors with a brief semi-structured interview; d) assessing HRV under baseline and stressed conditions; e) collecting self-report questionnaires; f) instructions on how to use the study equipment (smartphone and HR monitor) with demonstration and opportunities to practice; and g) paying participants.

After the first lab visit, the subsample (*n*=16) completed the at-home potion self-reporting data using EMA on the study smartphone app. Self-reported measures of stress and binge eating behaviors were collected before and after eating (3-8 times per day) and at the end of the day. The fourth day of the at-home protocol required participants to take photographs of food they were about to eat using the study smartphone app. Participants were asked to wear the HR monitor on the sixth day of the at-home protocol, pressing a button on the HR monitor before each meal or snack. The overall protocol was designed to fully capture essential constructs of interest while minimizing participant burden, thus maximizing adherence to the study data collection protocol. The study attempted to limit the extent to which interaction with the smartphone changed eating behavior. Participants in the at-home protocol returned for a second lab visit to return equipment, be debriefed about the study, engage in a semi-structured interview, and complete questionnaires about the experience in the study. Data captured during the seven day at-home protocol were stored on the HR monitors and smartphone and were downloaded by study staff to secure servers at the second lab visit.

Sample and setting

Recruitment and power

Participants with obesity were recruited through internet advertising (e.g., craigslist, electronic mailing lists); flyers posted at local coffee shops, stores, and libraries; letters and flyers sent to local clinics, private practice psychologists, and community-based overeating support groups; and contacting participants from previous research projects. The study recruitment materials initially described the study as a project aiming to understand the links between heart health behaviors. Participants were compensated for their time and transportation costs with a gift card to a local store and received $30 for the first lab visit and $85 for the at-home portion and second lab visit. To increase recruitment, the materials were modified to state that the study aimed to understand the relationship between stress and overeating. The compensation was also modified such that payment was in cash, and participants were given $60 for the first lab visit and $60 for the at-home portion and second lab visit. As recruitment took place from the general population of individuals with obesity living in San Diego, we anticipated the sample would have similar demographic characteristics to the population of San Diego (US Census Bureau, 2015): 47.2% White alone, not Hispanic or Latino, 32.9% Hispanic or Latino, 11.7% Asian, 5.6% Black or African American; 85.4% High school graduate or higher; median household income $63,373. We had intended to recruit equal numbers of male and female participants, but due to time limitations for recruitment we enrolled all eligible participants regardless of sex.

Power analyses were performed *a priori* to determine the sample size needed to achieve sufficient power. To evaluate the statistical power for Aim 1, we conducted power analyses using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). Data from Messerli-Burgy and colleagues' (2010) study of LF power HRV at baseline and when stressed in individuals who binge eat was used to calculate an effect size. Given an alpha = .05, a large effect size of $d = 0.74$, and power of .8, a total sample size of 13 would be needed to detect an effect of stress on HRV, and for power of .95 the total sample needed would be 21. An effect size from Haedt-Matt and Keel (2011b) was used for *a priori* analysis of necessary sample size for the association between binge eating and stress/negative affect in individuals who binge eat. Given an alpha = .05, a large effect size of $d = 0.68$, and power of .8, a total sample size of 15 would be needed to detect an effect of stress on binge eating, and for power of .95 the total sample needed would be 25. With the sample size of 15 participants completing the at-home portion of the study, we were confident that our sample size for Aim 2 would be sufficient to provide adequate power and warrant publication as it is a comparable sample size to published EMA (Haedt-Matt & Keel, 2011a, 2011b) studies of eating behavior.

Inclusion and exclusion criteria

Participants met the following inclusion criteria included: 18-69 years; BMI of ≥ 30 kg/m^2; currently trying to lose weight; at least 4 episodes of overeating or loss of control over eating for the previous four weeks; at least one rating of 2 or higher on the 4-item Cohen Perceived Stress Scale (PSS; Cohen & Williamson, 1987) to indicate the presence of some stress; and willingness to use either the study smartphone or their own Android™ smartphone if selected for the at-home portion of the study. Participants were excluded if they had serious or unstable medical or psychiatric illness (e.g., current unmanaged psychosis, mania), anorexia nervosa, bulimia nervosa, recreational drug use, or high risk for substance abuse as assessed with the Alcohol Use Disorders Identification Test (AUDIT-C) (Bush, Kivlahan, McDonell, Fihn, & Bradley, 1998) or psychosocial instability (e.g., homelessness) that could compromise study participation; conditions in which weight loss will be detrimental to one's health (e.g., pregnancy); current suicidal ideation or history of suicide attempt within 5 years; pharmacotherapy for obesity (e.g., Orlistat or Meridia) or bariatric surgery within the past 6 months; current use of beta-blocker medications; current tobacco use; medical conditions such as cardiovascular disease, cardiopulmonary problems, endocrine disorders, and autoimmune disorders; sleep apnea or high risk of sleep apnea identified by the STOP-BANG questionnaire (Chung, Yang, Brown, & Liao, 2014; Chung et al., 2008) and no current treatment for sleep apnea; or being unable to adhere to rules regarding exercise and consumption of food, alcohol, and caffeine before the first lab visit.

Measures

First lab visit

Participants were asked to refrain from eating, drinking alcohol or caffeinated beverages, and exercising 2 hours before the first lab visit to minimize the impact of digestion, sedation, and stimulation on the HRV assessment (Davies, Colhoun, Coats, Piepoli, & Francis, 2002; Friederich et al., 2006; Messerli-Burgy et al., 2010). At the first lab visit, participants underwent assessments of anthropometrics, binge eating behaviors, and HRV, were shown how to use the study smartphone app and HR monitor, and filled out self-reported questionnaires. Anthropometric assessment included obtaining participants' height and weight (Scale-Tronix 5002 Stand-On Scale) with clothing on and shoes off, hip and waist measurements, and blood pressure (Omron HEM-712C). The researcher (Kathryn M. Godfrey), a trained interviewer, administered the BED module of the Eating Disorder Examination Interview (EDE) (Cooper & Fairburn, 1987; Fairburn, Cooper, & O'Connor, 2008) 16th edition to assess BED according to DSM-5 criteria as a means of characterizing the sample. The EDE has demonstrated adequate test-retest reliability of binge eating episodes and long term recall and discriminant and convergent validity (Berg, Peterson, Frazier, & Crow, 2012). The interviewer assessed the additional binge eating behaviors of interest for this study (consumption of non-nutritious, high calorie foods, and breaking dietary rules) in the style of the EDE.

Participants were fit with a HR monitor and taken to a soundproof testing room for HRV recordings. A tablet computer presented a video with audio and text that guided participants through the instructions and recording protocol. Participants had an opportunity to practice pressing the buttons on the HR monitor and performing the paced breathing task. They had numerous opportunities to ask questions or clarify the instructions with the researcher before starting the protocol. The protocol consisted of 5 minutes each of: 1) baseline recording; 2) self-relaxation; 3) paced breathing condition (metronome breathing to 6 breaths per minute); 4) mental stressor (Serial 7 paradigm to activate sympathetic functioning); and 5) recovery. Mental math is the most commonly used mental stressor for inducing psychological stress and studying physiological reactivity (Brindle, Ginty, Phillips, & Carroll, 2014) and has several benefits over other methods such as a public speaking task or a reaction time test as it can be performed in a short period of time without specialized equipment. The HR monitor used was a commercially available portable psychophysiology device (Hidalgo Equivital™ LifeMonitor), which has demonstrated sufficient reliability and validity for assessing numerous psychophysiological measures (Liu, Zhu, Wang, Ye, & Li, 2013) and has companion software (VivoSense) to extract and analyze data with standardized methods. The HRV assessment protocol was developed from and analyzed using recommended and previously used procedures (Davies et al., 2002; Nolan et al., 2005; Task Force of The European Society of Cardiology and the North American Society for Pacing and Electrophysiology, 1996).

Upon completing the HRV protocol and leaving the testing room, participants removed the HR monitor and received instructions on how to use the study equipment (smartphone and HR monitor) with demonstrations, written study materials (Figure 2), opportunities to practice. They received training to properly rate the eating behavior items (Figure 2). The participants then self-reported their experience using the smartphone app and HR monitor (see Appendix A). These self-report measures assessed the participants' satisfaction, difficulty/ease of use, and likelihood to use study systems. The System Usability Scale (SUS; Brooke 1996), which is a well-used measure of usability with adequate psychometric properties (Bangor, Kortum, & Miller, 2008), generated an overall usability score for the system (smartphone to answer questions and take pictures, HR monitor). Participants completed a self-report measure packet encompassing demographic information, a medication list, and a list of medical conditions. The packet also measured smartphone attitudes with the Computer Attitude Scale (CAS; Nickell & Pinto, 1986), which has demonstrated adequate test-retest reliability and construct and predictive validity (Rainer & Miller, 1996). This scale was modified for smartphones (Appendix B), and a similarly modified version has been used by other researchers (King et al., 2013). In this sample, the modified version of the CAS had moderate internal consistency (Cronbach's alpha = 0.60). Smartphone self-efficacy was assessed with the Computer Self-Efficacy measure (CSE; Compeau & Higgins, 1995) modified for smartphone applications (Appendix B). Although the psychometric properties of the CSE have not been well studied, it had high internal consistency (Cronbach's alpha = 0.89) within the current sample. The Dutch Eating Behavior Questionnaire (DEBQ; Van Strien, Frijters, Bergers, & Defares, 1986) and the Binge Eating Scale (BES; Gormally, Black, Daston, & Rardin, 1982) assessed eating disorder symptoms. Both measures have demonstrated good psychometric properties (Cotter & Kelly, 2015; Wardle, 1987) with high internal consistency within the current sample (BES Cronbach's alpha = 0.85, DEBQ restrained eating Cronbach's alpha = 0.89, DEBQ emotional eating Cronbach's alpha = 0.97, DEBQ external eating

Cronbach's alpha = 0.81). Mental health symptoms were assessed with the PTSD Checklist – Civilian Version (PCL-C; Blanchard, Jones-Alexander, Buckley, & Forneris, 1996), the Patient Health Questionnaire-9 (PHQ-9; Kroenke, Spitzer, & Williams, 2001), the Generalized Anxiety Disorder-7 scale (GAD-7; Spitzer, Kroenke, Williams, & Lowe, 2006), and the Positive and Negative Affect Schedule (PNAS; Watson, Clark, & Tellegen, 1988). All of these measures have demonstrated sufficient psychometric properties (Crawford & Henry, 2004; Kroenke, Spitzer, Williams, & Löwe, 2010; Wilkins, Lang, & Norman, 2011) with high internal consistency within the current sample (PCL-C Cronbach's alpha = 0.90, PHQ-9 Cronbach's alpha = 0.84, GAD-7 Cronbach's alpha = 0.92, PNAS PA subscale Cronbach's alpha = 0.94, PNAS NA subscale Cronbach's alpha = 0.84). The Brief Pain Inventory (BPI; Cleeland & Ryan, 1994) is a measure that has demonstrated adequate psychometric properties (Tan, Jensen, Thornby, & Shanti, 2004) with high internal consistency in the current sample (BPI severity Cronbach's alpha = 0.85, BPI interference Cronbach's alpha = 0.94). Stress was measured with the Cohen Perceived Stress Questionnaire 10 item version (PSS-10; Cohen, Kamarck, & Mermelstein, 1983), which has sufficient psychometric properties (Lee, 2012) and high internal consistency within this sample (Cronbach's alpha = 0.84). A commonly used measure, the International Physical Activity Questionnaire (IPAQ; Craig et al., 2003), assessed physical activity. Calculations of metabolic equivalent task (MET) outcomes followed the standard protocols (Craig et al., 2003). Although there is some evidence that the IPAQ overestimates physical activity, especially in sedentary populations (Fogelholm et al., 2006), it demonstrates comparable psychometrics relative to other brief self-reported physical activity measures (Jacobs, Ainsworth, Hartman, & Leon, 1993).

After completing the self-report questionnaires, participants were told into which group they had been assigned and provided with payment for the visit. Assignment was done at using a random number generator in Excel, when possible, and also took into account scheduling conflicts, technological problems, and participant preference (i.e., if they did not want to complete the second part, they did not get assigned into the EMA group). Participants assigned to do the at-home portion of the study and second lab visit were given a binder with written instructions how to use the smartphone app and HR monitor. Participants were given the choice to use their personal smartphone, if it was an Android™ or use a study smartphone for the seven day at-home portion of the study. The smartphones were set up with the app, and participants had a chance to ask the researcher questions to ensure they understood the procedures for the at-home portion. They were also given the choice to have text and/or email reminders for days 4 and 6 and for the second lab visit.

At-home protocol

Participants who underwent the at-home protocol completed the set of EMA self-report questions specially designed for this study. The EMA self-report measures were presented either on the study smartphone or on participants' personal smartphones using movisensXS application for Android™. The home screen of the smartphone had three buttons ("Just about to eat?"; "Just finished eating?; "End of the day follow up") to allow participants to complete the self-report questionnaires at appropriate times (Figure 3). Participants followed an event contingent EMA sampling procedure by completing self-reported measures of stress and eating behaviors on the smartphone before and after every time they ate (meals and snacks) during the seven days. To capture any other relevant data, they also completed one series of self-report questions before they went to bed each night.

Participants were asked to press the “Just about to eat?” button before eating each meal or snack during the seven days of the at-home protocol. Pressing the “Just about to eat?” button presented the participant with the PSS 4-item version (PSS-4; Cohen et al., 1983). The PSS-4 has demonstrated satisfactory psychometric properties and is recommended for use as a measure of stress in studies that have limited time for self-reporting (Cohen et al., 1983). Each of the four items asks about how often certain feelings or thoughts have been experienced and presents responses that range from “never” to “fairly often" (as in Figure 4). Given the frequency of stress assessment using the PSS-4 in this study, the time frame was set to “since you last ate,” which is similar to time frame modifications used by other EMA studies using the PSS (Carney, Armeli, Tennen, Affleck, & O'Neil, 2000; Rydin-Gray, 2007). For the fourth day of the at-home protocol, participants were asked to take photos of their food before they ate. Participants were trained on how to take photos of the food they were eating to avoid including any identifying information in the images (Figure 5B-C). On the other days of the at-home protocol, participants could skip this section and take photographs of their food only if they chose. The images were used later by researchers to validate the self-reported binge eating behaviors. A final screen provided a reminder to complete the next self-report measure after having eaten (Figure 5D).

Participants were asked to press the “Just finished eating?” button after each time they ate. Pressing the “Just finished eating?” button displayed the binge eating behavior measure. This measure allowed participants to report if they engaged in any of the following binge eating behaviors: overeating, loss of control, eating non-nutritious/high calorie foods, non-adherence to dietary rules, or none of the above eating behaviors (Figure 6A). These binge eating behavior items were selected to represent important components of binge eating under the RIM. Of these four items assessing the presence of unhealthy eating behavior, two items (overeating and loss of control) were from the EDE-Q (Fairburn & Beglin, 2008), one item inquiring about breaking dietary rules was modified from the EDE-Q, and one item was created in the style of the EDE-Q items inquiring about consumption of non-nutritious, high calorie foods such as potato chips, burgers, pizza, hot dogs, fried foods, soda, or sweetened drinks based on a list of foods likely to be eaten when stressed or when overeating (Arikian et al., 2012; Groesz et al., 2012). These items are similar to eating behavior assessments conducted in other published studies of eating using EMA (Carels, Douglass, Cacciapaglia, & O'Brien, 2004; Goldschmidt et al., 2014). The item assessing eating non-nutritious, high calorie foods was intentionally limited compared to other EMA studies of eating behavior using electronic food diaries (Fukuo et al., 2009; Kikuchi et al., 2011) because the precise estimates of dietary nutrition content was not a main outcome of interest. The assessment did not assess exact caloric intake, foods consumed, or macronutrients to limit the extent of disruption from self-monitoring on natural eating behavior. The item asking about breaking dietary rules was included to allow for examination of potential abstinence violation effects, which have been implicated in binge eating

(Arnow et al., 1992). A final screen provided a reminder to participants to complete future self-report measures before eating (Figure 6B).

Participants were asked to press the “end of the day follow up” button at the end of each at-home day to be presented with three open response questions about their study experience that day. The first question asked about any eating they forgot to record (Figure 7A). The second question inquired if recording eating caused them to change their eating behaviors (Figure 7B). The last question asked about any problems encountered with the smartphone app or HR monitor (Figure 7C).

Participants wore the HR monitor on day six of the at-home protocol. HRV data were collected continually when the participants were wearing the portable device. Participants were asked to press the button on the HR monitor before eating in order to flag times in the HRV data when they were eating. Given the numerous variables (posture, level of activity, etc.) that influence HRV data quality during a naturalistic collection, data collected during the at-home protocol were not used for analysis. The HRV data collected during this time were examined for a preliminary determination of data quality to inform future studies with designs to collect ambulatory HRV data.

Second lab visit

Participants who attended the second lab visit returned study equipment and shared information about their experience in the study. Participants’ experience (Aim 3) was assessed using a 42-item self-report measure (Appendix C) and a semi-structured interview (Appendix D) specifically created for this study. The self-report measures assessed the participants’ satisfaction, difficulty/ease of use, expectations, and likelihood to use study systems. The SUS assessed overall usability for the system (smartphone to answer questions and take pictures, HR monitor). Other items inquired about remembering to answer study questions and the comfort of the HR monitor. Additionally, the questionnaires asked participants about any abnormal circumstances or changes to their normal routines that might have impacted their stress or health behaviors. The semi-structured interview was conducted by the researcher (KMG) after completion of the self-report questionnaires and was audio recorded. This interview asked open-ended questions about the participants' experience in the study, their ability to remember to use the devices, how easy and comfortable the devices were to use, any problems they encountered, what they liked or disliked about the study, any suggestions on who might benefit from using the study technology, and ideas about future stress and eating research. The researcher (KMG) also presented three scenarios that allowed the participants to comment on different clinical applications of the study system. One scenario presented the potential clinical utility of providing individualized feedback based on an assessment of stress and eating. Another scenario displayed a smartphone-based alerting system to warn users of increased risk for unhealthy eating. The final scenario described a potential smartphone-based alerting system plus a just-in-time adaptive intervention to reduce stress. Open ended questions about these scenarios asked participants their impression of these different applications, how useful the systems might be, and how interested they would be in using these systems for short and long periods of time.

Data processing

Data were prepared and cleaned prior to data analysis to ensure proper data entry and to examine any potential technological problems. All questionnaire data were entered into a Microsoft Access database by a research assistant then moved into SPSS by the researcher (KMG). Interview recordings were transcribed verbatim and prepared for analysis by the researcher (KMG).

EMA data were processed to identify eating episodes according to a set protocol determined by the researcher (KMG). This protocol was based on previously reported methodology (Elmore & de Castro, 1990; Engelberg, Steiger, Gauvin, & Wonderlich, 2007; Ranzenhofer et al., 2016), when possible, and modified to address the specifics of the study methodology and data and to limit excluding eating data from analysis. Self-report measures taken before ("just about to eat?") and after ("just finished eating?") eating were grouped together in a single eating episode if they were completed by the participant within 3 hours of each other. This timeframe gave participants a liberal window to remember to complete the after eating measure while also assuming that before and after eating measures occurring outside this window were separate eating episodes. If these two measures were completed within 10 minutes of each other, the order of the surveys did not matter (i.e., after eating survey could precede the before eating survey). Multiple eating episodes that were very close in time (e.g., within 30 mins) were treated as a single episode. This rule aligns with instructions given to participants to allow for continued data entry if an eating episode continued even after they submitted an after eating questionnaire as they may not have always known the precise end of the eating episode.

EMA data were examined for duplicate or missing entries. Measures were considered duplicate if they were entered in close proximity to a measure with identical data. Measures with non-identical data within the same eating episode were merged by taking the mean of the two scores (e.g., a PSS-4 total score of 3 and 4 were merged to give that eating episode a PSS-4 total score of 3.5). Missing measures were identified if the counterpart measure (e.g., before eating measure completed without an after eating measure) did not happen within the 3 hour timeframe.

Photo-validation for ratings of overeating and non-nutritious, high calorie foods was performed by the researcher (KMG) examining all photos of food that participants took during the seven day at-home period. The researcher rated each photo as either episodes (e.g., overeating present) or non-episodes (e.g., overeating absent) according to the study protocol and instructions given to participants. Ratings were collected into two separate 2x2 tables that included participants' and the researcher's ratings. The researcher then examined the frequency with which participants identified or misidentified these episode types.

HRV data were processed using VivoSense software (version 2.9) to obtain the time and frequency domain variables. Each recording session was broken into the 5 minute segments corresponding to the different parts of the psychophysiological assessment protocol, which were analyzed separately. The VivoSense software's automatic artifact detection was used to determine the presence of noise or artifacts that might lead to excluded or interpolated data. For the data collected in the lab, segments with more than one marked artifact, excluded data point, or interpolated data point in one minute were considered poor quality and were excluded from analysis. The research assistant also performed a brief visual inspection of the data to examine potential issues with the signal and data quality and to ensure that the software's automatic Q wave, R wave, and S wave (QRS complex) detection had occurred properly. Values for HRV variables were compared to values found previously to highlight potentially erroneous data (Task Force of The European Society of Cardiology and the North American Society for Pacing and Electrophysiology, 1996; Zhang, 2007). As done in prior research (Ranzenhofer et al., 2016), HRV data collected from the at-home portion of the study was cut into 30 minute segments before an event marker, which signaled an eating episode. These segments were examined for data quality, including number and proximity of artifacts and interpolations. Under the data quality protocol for this study, segments with more than one excluded or interpolated data point in one minute were considered poor quality. All other data were considered of sufficient quality for analysis.

Relevant sociodemographic, clinical, psychophysiological, and behavioral variables were examined to characterize the sample. Manipulation checks using repeated measures ANOVA were performed on the HRV data to examine differences in HRV variables at baseline and when stressed. For aim 1 analyses, distributions of HRV variables were examined for non-normality using Q-Q plots and Kolmogorov-Smirnov tests. HRV variables with positively skewed distributions were natural log (ln) transformed whereas variables with negatively skewed distributions were transformed with exponent functions. After these transformations, all variables were normally distributed. Analyses were run with both non-transformed and transformed HRV variables. If findings were not changed with transformed HRV variables, results of the analyses using non-transformed variables were presented for ease of interpretation. Models with transformed variables are shown only if they produced different findings relative to models with non-transformed variables.

Data analysis

Statistical methods varied for each aim.

Aim 1. Binge eating behaviors from the previous four weeks and from the seven day at-home protocol were summed separately to produce frequencies of each binge eating behavior for the two time periods assessed. Two sets of multiple linear regression models were run. The first set of multiple linear regression models examined if frequency of binge eating behaviors during the four weeks before the lab visit (predictor) were related to HRV variables at baseline and when stressed (outcome). The second set of multiple linear regression models examined if frequency of binge eating behaviors during the at-home protocol (predictor) were related to HRV variables at baseline and when stressed (outcome). Sex, BMI, age, use of psychotropic medications (e.g., antidepressants), type I and type II diabetes, physical activity levels measured with the IPAQ, and self-reported stress in the past month from the PSS-10 at the baseline assessment were considered as potential covariates in the models for Aim 1. Models with significant findings were inspected for influential cases and the assumptions of regression models. Cases with influence (i.e., leverage times distance) were examined with Cook's D statistics. No cases presented values of Cook's D > 1. Assumptions of the regression models were examined to ensure there were no violations. Visual inspection of histograms revealed that all residuals were approximately normal. Scatterplots of residuals by predicted values were examined to ensure no violations of homogeneity of variance were found. These models were also checked for multicollinearity issues to confirm all tolerance values were at least .25, which corresponds explanatory variables correlated at $r^2 = .75$ or less. We hypothesized that higher frequency of binge eating behaviors reported for the four weeks before the first lab visit and during the seven day at-home protocol would be significantly associated with lower HRV at baseline and when stressed.

Aim 2. Longitudinal multilevel mixed effects models were used to determine if stress reported in the "about to eat" measure (predictor) was associated with binge eating behaviors (outcome) during the seven day at-home data collection period. These models included separate predictors to specify the within-participant process of change in self-reported stress and the between-participant differences in average level of self-reported stress. These two variable were generated from the grand mean centered PSS-4 total score variable. Sex, psychological variables such as depression, anxiety, and PTSD symptoms, pain symptoms, and technology attitudes and self-efficacy were considered as potential covariates in the Aim 2 models. We hypothesized that within an eating episode higher self-reported stress would be significantly associated with increased probability of binge eating behaviors.

For aims 1 and 2, an alpha of .05 was used for all models. Statistical analysis were conducted using SPSS 23 (IBM).

Aim 3. For this aim, qualitative data analyses were performed on data from semi-structured interview data. Due to the relatively limited literature on how clinical populations perceive and use mobile technologies for assessing stress and binge eating, qualitative analyses were conventional content analysis with an inductive approach to identify themes and describe the common participant responses (Hsieh & Shannon, 2005). The qualitative content analysis was conducted in two phases: the first phase involved examining the responses, determining the units of analysis and codes, and conducting preliminary and final coding; the second phase identified categories and themes and drew interpretations (Roller & Lavrakas, 2015). All coding was performed by the researcher (KMG). To ensure validity of the codes generated and the codebook structure, a consulting researcher who has extensive experience with both binge eating research and qualitative methods but is not affiliated with the project examined a preliminary draft of the codebook and several de-identified interview transcripts to engage the researcher (KMG) in discussion around the interpretations made. This consulting researcher and to provide comments, edits, and perspective on the codebook prior to the final coding of the transcripts to ensure validity. The codes were organized according to two main research questions: 1. What were participants' experiences as a result of participating in the study (eating behavior, smartphone, HR monitor)?; 2. What suggestions do participants have to improve the study, conduct future research, or apply these devices for clinical work? The codebook continued to be refined during coding to ensure accurate representation of the data. The final version of the codebook (Appendix E) provided the codes, organized by research questions and clustered themes, definitions of the codes, and examples from the transcripts that were given each code. Data were coded using QDA Miner Lite v2.0 (Provalis Research), which generated tables to examine the overall frequency of each code used and the number of participants with transcripts containing each code.

Item response counts were presented to quantitate items from the self-report measures. A total SUS score was calculated and interpreted. Further, we examined the quality of the HRV data (artifact and interpolations) from day six of the at-home data collection to determine if the HRV data collected naturalistically is of sufficient quality to be analyzed. We had no hypotheses for aim 3.

Results

Participants

Recruitment occurred from September 2015 to April 2016. Figure 8 presents the flow chart for recruitment and study participation. Of the 235 individuals screened, 196 were ineligible mainly due to BMI, overeating/loss of control, and stress under required thresholds or substance use, exclusionary medical/psychiatric problems, and uncontrolled sleep apnea. Thirty-four individuals of the 39 eligible after screening were consented for the study. One consented participant did not complete the first lab visit as it was determined that she had lost weight since screening and no longer met the study's BMI inclusion criteria. The other participant who did not complete the first lab visit asked to end the session during the HRV recording due to discomfort during the stressor (serial 7 task). Sixteen of the 32 participants who completed the first lab visit were assigned to the at-home protocol, including the at-home portion and second lab visit. One participant assigned to the EMA group opted out for personal reasons, and one participant was not able to be in the EMA group due to technological problems with the movisensXS website that day. All participants assigned to the EMA group returned for the second lab visit. Participant recruitment continued after reaching goal numbers for each group because we attempted to get at least 30 total participants with good quality HRV data for analysis.

The demographic characteristics for the sample that completed the first lab visit are presented in Table 2. The sample was mostly female, non-Hispanic/Latino white or African American, single, with either some college or a Bachelor's degree. The sample was fairly evenly distributed in terms of the household income.

Descriptive Characteristics

Table 3 presents the eating behavior characteristics for the sample. Thirteen (40.6%) of the 32 participants met DSM-IV criteria for BED; fifteen (46.9%) met DSM-5 criteria for BED. Eating behavior characteristics by diagnostic group are presented here for descriptive purposes. As the study did not aim to recruit specifically for BED diagnosis, analyses comparing participants who met and did not meet criteria for BED are not performed. On average, participants reported that over the four weeks prior to the first lab visit they had 25 episodes of eating non-nutritious, high calorie foods, 16 episodes of breaking dietary rules, 11 loss of control episodes, and 6 overeating episodes. Mean scores on the BES were above suggested cutoff score (non-binge eaters ≤17) previously used by other authors (Greeno, Marcus, & Wing, 1995). Participants in this study scored higher on all subscales of the DEBQ (restrained, emotional, and external eating) compared to a sample of individuals with obesity (Van Strien et al., 1986).

The most common non-nutritious, high-calorie foods that participants reported eating in the previous four weeks were chips, burgers, French fries, pizza, soda, fried foods, Mexican foods, ice cream, fast food, and chocolate/candy (see Table 4). As Table 5 displays, participants reported following a variety of dietary rules. The most common were rules related to avoiding certain types of food (e.g., no sugary foods, no fried foods, no candy), limiting calories, points, or macronutrients, watching portion sizes, and restricting when they eat (e.g., no snacking between meals, no eating in the morning). Table 6 provides the quantitative summaries of EMA data collected during the at-home portion of the study. On average, participants performed the at-home portion for across more than 7 full days or 24-hour periods. The 16 participants reported a total of 340 eating episodes during the at-home period of the study with each participant recording about 3 eating episodes per day. Participants' average self-reported stress was 6 of the maximum 16 points on the PSS-4. Although participants, on average, logged more eating episodes without any of the binge eating behaviors of interest, the most common binge eating behaviors participants endorsed were non-nutritious, high calorie foods and overeating followed by breaking dietary rules and loss of control.

Results of the photo-validation for overeating and non-nutritious, high calorie episodes demonstrate that participants were accurate at rating a researcher rated non-episode but were less accurate when rating researcher rated episodes. For overeating, there were 95 photos that the researcher rated as a non-episodes, of which 81 (85%) were correctly rated by participants as non-episodes, leaving 14 (15%) that participants inaccurately rated as overeating episodes. There was only one photo that the researcher identified as an overeating episode and the participant correctly labeled it as an overeating episode. For rating of non-nutritious, high calorie foods, there were 75 researcher identified episodes, of which 70 (93%) participants rated as non-episodes, leaving 5 (7%) of non-episodes that participants falsely rated as episodes. The researcher identified 38 episodes of non-nutritious, high calorie foods, of which 21 (55%) participants correctly rates as episodes, leaving 17 photos (45%) that were inaccurately rated as non-episodes. Due to the limited number of days of photos taken and the relative infrequency of binge eating behaviors during the seven days at-home, all self-reported binge eating behaviors were considered for inclusion in statistical models rather than including only photo-validated episodes. Results of photo-validation analysis are still provided to capture how well participants rated different types of eating episodes, which may serve future EMA studies of binge eating.

Aim 1: Eating behaviors and HRV analysis

Overall, about 12% of the data collected at the first lab visit did not meet our data quality standards to be included in the analyses. Half of these data quality issues were due to abnormalities in 2 participants' QRS complex, whereas the other half were due to HR monitor technical issues such as large amounts of artifact, excluded data, data interpolation, or the monitor turning off. Descriptives of the HRV and HR variables from the lab protocol are presented in Table 7. RMSSD, HF, LFn, HFn, LF/HF ratio were all statistically significantly different between baseline and serial 7 conditions whereas SNDD, VLF, LF, and HR were not different between conditions.

All binge eating behaviors from the previous four weeks assessed with the EDE demonstrated positive correlations of weak to moderate magnitude, except for the correlation between loss of control and breaking dietary rules (see Table 8). Many of the HRV variables at baseline were strongly correlated (see Table 9). Given that the eating behavior variables were not strongly correlated but the HRV variables at baseline were strongly correlated, models included all eating behaviors together as explanatory variables together with each HRV variable separately as an outcome to avoid multicollinearity in regression models.

Only one participant reported current use of psychotropic medications, and only two participants said they had type II diabetes. Therefore, these variables were not considered as potential covariates in the models. Bivariate correlations were examined between all HRV variables, HR, and age, BMI, self-reported stress on the PSS-10, and physical activity levels from the IPAQ. Results from these correlation analyses are presented in Table 10. The only statistically significant correlation was between BMI and HR (Pearson r = 0.53, p = 0.002) such that participants who had higher BMI also tended to have higher HR at baseline. One-way analysis of variance (ANOVA) models were run to examine differences in HRV variables and HR by sex. Due to the potential for violating the homogeneity of variance assumption, especially given the substantial difference between the number of female versus male participants, robust tests were run to produce a Welch test statistic for the ANOVA models. Results of the ANOVA models are displayed in Table 11. Significant sex differences were found for LFn, Welch F (1, 9.31) = 11.70, p = 0.007, HFn, Welch F (1, 9.38) = 10.14, p = 0.011, and LF/HF ratio, Welch F (1, 6.47) = 7.58, p = 0.031. Therefore, BMI was included as a covariate in models of HR, and sex as a dummy coded variable was included as a covariate in models with HRV for aim 1 analyses.

Table 12 displays results of regression models with previous four weeks' binge eating behaviors and baseline HRV and HR. Statistically significant associations were found between baseline SDNN and loss of control, B = -1.26, t = -2.26, p = 0.03, sr^2 = 0.15, between baseline lnHF and loss of control, B = -0.06, t = -2.21, p = 0.04, sr^2 = 0.13, and between baseline LFn and overeating, B = 0.01, t = 2.08, p = 0.04, sr^2 = 0.11. Participants who had higher values on SDNN at baseline reported fewer episodes with loss of control in the previous four weeks. Those with lower natural log transformed values of HF at baseline had more loss of control episodes in the previous four weeks.

Participants with higher LFn values at baseline had more episodes of loss of control over eating in the previous four weeks.

Table 13 presents the results of regression models with previous four weeks' binge eating behaviors and the mental stressor (serial 7 task) HRV and HR. None of the eating behavior variables was significantly associated with any of the HRV or HR variables. Results of regression models with at-home binge eating behaviors and baseline HRV and HR are presented in Table 14. None of the eating behavior variables was significantly associated with any of the HRV or HR variables. However, association between at-home episodes of overeating and HR, *B* = -2.64, *t* = -2.12, *p* = 0.07, sr^2 = 0.24, approached significance.

Table 15 displays results of regression models with at-home binge eating behaviors and serial 7 HRV and HR. The association between at-home episodes of non-nutritious, high calorie foods and HF approached significance, *B* = -473.61, *t* = -2.12, *p* = 0.07, sr^2 = 0.32, but none of the other models had statistically significant relationships. Statistics from the overall models are not included as accounting for overall variance in HRV and HR is not an aim of interest to this study and overall model significance may be due to inclusion of covariates (i.e., sex, BMI).

Aim 2: Eating behaviors and stress analysis

Individual trends of stress and binge eating behaviors across the seven days of the at-home portion of the study are displayed in Figure 9 and Figure 10, respectively. Visual inspection of the panel plots for stress over time revealed no apparent reactivity to self-reporting stress levels through EMA. Similarly, reactivity for reporting binge eating behaviors was largely absent, with the exception of one participant who reported two episodes of binge eating behaviors early in the at-home period and none during the remainder of the EMA data collection.

To determine possible covariates to include in the models, bivariate correlations were examined between all at-home binge eating variables and scores on the PHQ-9, GAD-7, PCL-C, smartphone attitudes, and smartphone self-efficacy scales. Results from these correlation analyses are presented in Table 16. The only statistically significant correlations were between episodes of loss of control and GAD-7 (Pearson $r = 0.64$, $p = 0.007$) and PCL-C (Pearson $r = 0.52$, $p = 0.042$) such that participants who had higher anxiety and PTSD symptom scores also tended to have higher number of episodes of loss of control during the at-home period. One-way ANOVA models were run to examine differences in at-home binge eating variables by sex. Due to the potential for violating the homogeneity of variance assumption, especially given the substantial difference between the number of female versus male participants, robust tests were run to produce a Welch test statistic for the ANOVA models. Results of the ANOVA models are displayed in Table 17. No significant differences were found between the number of binge eating episodes reported during the at-home period between female and male participants. Therefore, only GAD-7 and PCL-C scores were included as covariates in the model of loss of control for aim 2 analyses.

Results of the multilevel model of overeating as a function of PSS-4 score during the seven day at-home period are presented in Table 18. The within participant PSS-4 variable was significantly associated with increased chance of overeating ($OR = 1.19$, $p = 0.011$). Figure 11 displays a scatterplot of the model's predicted probability of overeating by self-reported stress with a linear trend line demonstrating an increased chance of overeating with increased stress. At an average hour for a participant with an average level of stress across all eating episodes, the model predicted that the probability of overeating is 4% when the PSS-4 total score is 6 points below average, 10% when PSS-4 total score is at his/her average, and 23% when the PSS-4 total score is 6 points above average. The random effects show the size of the residual variance, which supported only limited evidence for autocorrelation in this model.

Table 19 displays the results of the multilevel model of loss of control as a function of PSS-4 score during the seven day at-home period, controlling for anxiety (GAD-7) and PTSD symptoms (PCL-C). The within participant PSS-4 variable was significantly associated with increased chance of loss of control (*OR* = 1.45, $p < 0.001$). Given that the included covariates were not statistically significant, the model was run without covariates with results presented in Table 20. In this model, the within participant PSS-4 variable remained significantly associated with increased chance of loss of control (*OR* = 1.40, $p < 0.001$). Figure 12 shows a scatterplot of this model's predicted probability of loss of control over eating by self-reported stress with a linear trend line demonstrating an increased chance of loss of control with increased stress. At an average hour for a participant with an average level of stress across all eating episodes, the model predicted that the probability of loss of control over eating when a PSS-4 score is on a participant's average or below is less than 1%, and a PSS-4 total score 10 points higher than average is associated with a 7% chance of loss of control. The random effects examined the magnitude of the residual variance and suggest that there may be evidence of autocorrelation within this model.

Findings from models of non-nutritious, high calorie foods and breaking dietary rules are shown in Table 21 and Table 22, respectively. Neither demonstrate a significant association between the within participant PSS-4 scores and likelihood of these eating behaviors.

Aim 3: Participant experience and feasibility

Adherence and usability

Based on EMA data collected (Table 6), participants recorded around three eating episodes per day with one day missed, on average. Participants recorded at least one episode for 83% of the days. The second questionnaire (after eating *M* missed = 3) was more likely to be missed relative to the first questionnaire (before eating *M* missed = 1). End of the day follow up surveys were completed approximately 79% of the time expected. The number of days that photos were taken (*M* days = 3) exceeded the required one day. Self-reported compliance to the at-home portion of the study was also assessed at the second lab visit with 14 of the 16 participants reporting average daily compliance between 75-100%. Of the two remaining participants, one reported compliance between 50-75% and the other reported compliance with EMA questionnaires at 25%.

The SUS was given to all participants after completing training on the smartphone, HR monitor, and procedures for the at-home portion of the study. The mean SUS score was 85.31 (*SD* = 13.56, range 42.50-100), indicating that overall usability scores for the system were quite high. Only 4 of the 32 participants (13%) rated the usability lower than a 70 out 100 points on this scale. After doing the at-home portion of the study, the 16 participants completed the SUS again with a mean score of

81.15 (*SD* = 12.90, range 55-100). Only 3 of the 16 participants (19%) rated the usability lower than a 70 out 100 points on this scale. Usability ratings remained fairly constant, even after some participants had increased use during the at-home portion.

Figure 13 displays results from the satisfaction and usability questions given to participants at the first and second lab visits. At the first lab visit participants reported being generally satisfied with the instructions, found the smartphone and HR monitor easy to use and comfortable, would be likely to use the app if it also tracked diet in more detail, and would be likely to use the HR monitor if it could track their stress. At the second lab visit, participants remained satisfied with the instructions. They found the smartphone easy to use to answer questions but reported being more satisfied with the before and after eating questions than the end of the day follow up questions. They remained satisfied with taking photos of food and were equally interested in using the app for tracking their diet in more detail. Participants rated the HR monitor as somewhat lower in ease of use compared to the first lab visit, and ratings of comfort also dropped substantially after the at-home portion of the study. Similarly, their likelihood of using the HR monitor to track stress dropped somewhat between the first and second lab visits.

HRV data quality

Of the 16 participants that did the at-home portion of the study, 15 recorded HRV data. There were HRV data files from 3 participants that were corrupt and could not be opened by the HRV analysis software (VivoSense). The remaining files could be opened by the analysis software were split into segments that corresponded to the 30 minutes before an eating episode. The number of segments per participant ranged from three to nine in the single day of recording, meaning that participants flagged eating episodes between three and nine times that day. A total of 79 30 minute segments were derived from the 15 participants who recorded at-home HRV data. Of these 79 segments, 37 (46.8%) followed our rules for good data quality. The remainder of the segments did not meet our standards for good data quality as they were either completely marked as artifact by the automatic artifact detection software (17 segments, 21.5%) or had two interpolations of data within one minute (25 segments, 31.6%). The pattern of data quality appeared to be specific to each participant. For five of the 15 participants, none of their at-home HRV segments met the good data quality requirements. Another five participants had less than half of their segments meeting good data quality criteria. The remaining five participants had more than half of their segments meeting criteria for good data quality, but there was not a single participant with all of their segments meeting good data quality criteria.

Qualitative content analysis

Descriptives

All 16 participants who completed the at-home portion of the study did the semi-structured interview and agreed to have it audio recorded. Interviews lasted between 22 and 56 minutes (*M* = 35:52, *SD* = 9:47). The final codebook contained 45 codes that were organized into 11 categories. The codes and categories were divided by the two research questions: 1) What were participants' experiences participating in the study (eating behavior, smartphone, HR monitor), including suggestions for future research; 2) What are participants' reactions on proposed ways to use these devices clinically? The codebook with codes, categories, and examples from the data is provided in Appendix E.

Themes

There were numerous themes that emerged from the qualitative content analysis. The sections below present themes that were most common in the sample. The less common themes are not discussed in detail here but can be examined in the codebook (Appendix E).

Themes from the first research question. All participants shared that the study procedures and devices were simple and easy to use and often expressed positive emotions or feedback about their experience. One participant said of the study overall, *"The questions were simple. It was all pretty straightforward."* Similar responses were shared by other participants, for example, *"I know how to use smartphones so it was easy."* Positive emotions or feedback shared by participants pertained to the study in general ("*Overall very pleasant experience*.") or to specific aspects or features of the study ("*That was good, that was a good question*"; "*the buzzer option was good*"). All study participants also had neutral reactions to some element of the study or its procedures. Comments such as, "*It was fine*." and "*I'm pretty neutral about the rest of it*." were regularly shared. When asked about their experiences in the study, all participants provided suggestions for improvement of study tasks. These suggestions mostly pertained to the HR monitor, "*Find a different device for the HR monitor. By using a watch or something people would be more inclined to use it seven days a week. It's not so bulky. It looks like a watch. People would be more inclined to wear it seven days a week*." Participants also frequently suggested ideas to improve completion of questionnaires using reminders or a list of questionnaires completed, "*When you are doing it so many times and then you have a snack it would be nice to have something, or even an alert to say, "it's whatever time or have you eaten yet?" Some kind of alert that would help you remember, or at the end of the day, maybe at a time after when you normally would have had dinner it would check in and say it's 8 o clock or 9 o clock, have you done your final thing today*?"

There were several themes that were shared by almost all participants. Most participants found the HR monitor uncomfortable in some way. One participant described the experience of increased discomfort with long term wear, *"But after about hour five at home, it chaffed a little. And I don't know if that's because I wear an underwire, or just the placement, or where it has to sit because I'm female, but it was like I kept adjusting it all evening. It was like this thing is not comfortable, but it wasn't like unbearable."* Others tried to make it more comfortable but ultimately found it too much to wear, *"It seemed it was uncomfortable, and I know you demonstrated how to wear it. I had assistance making sure I put it on right. However, it was just too much."* Another nearly universal theme across participants was forgetting to complete the surveys on the smartphone app. Participants struggled most with remembering to complete the questionnaire after eating, *"I forgot to answer the questions after eating. But I reminded myself. I would look down and see it, put it in my purse right away so I knew I had it but something had to trigger me to pick it up to remind me to say ok, don't forget to put this in. It was after eating, that was the problem."* Participants often shared negative emotions or reactions to the study. They expressed a range of negative responses from overt dislike (*"I didn't like it.")* to embarrassment or discomfort (*"It's* *embarrassing, like oh that's a lot of food. I ate a lot of food"*; *"the questions were kind of uncomfortable"*) to annoyance (*"sometimes apps can go crazy so that one day it kept popping up and buzzing it was annoying"*). Equally common was the theme that the study tasks made participants more aware of their eating or more attentive when they were eating. One participant shared that the awareness of eating was related to feeling accountable, *"The accountability of making conscious decisions about eating because I knew I was either going to have to take pictures or answer the questions. That made eating more conscious than subconscious."* Some participants reported being more aware of the link between emotions and food choice, *"I think the before eating questions…really made me self-aware of how I was feeling and how those feelings translated into the foods I was choosing."* Another participant commented that taking pictures, specifically, increased awareness, *"But it helped because you're taking images of something you're about to partake in. It makes you think about your choices about what food you are about to eat and the amount."*

The majority of participants stated that they changed their eating and reviewed their eating habits due to the study procedures. Having to complete the questionnaires before eating sometimes interrupted or delayed eating as one participant said, *"It's not that big of a burden but surprisingly that having to think about it for a second made me a second to pause and sometimes it would sort of deter me and I'd think maybe I'll just wait for a little bit."* Another participant noted that logging food for the study helped her return to her intended diet, *"doing this really helped me get back to the way that I'd like to be eating and the way that I was eating before."* Review of food intake was frequently described as an opportunity to remember foods eaten and evaluate or reflect if eating was in line with goals. One participant stated, *"it was sometimes a little tricky to try to think back to a time when you grabbed an extra set of walnuts. Like when did I do that? How much did I have?"* Others remarked that reviewing their eating was a more evaluative process (*"it was a good reflection that gave me an opportunity to kind of evaluate."*; *"I could see how totally sloppy my food plan and abstinence was getting"*). Participants reported that reviewing eating habits was different when using the camera to take photos of food (*"Taking pictures of food just really makes you take into scope if it were a salad and if I took a picture of that how much better that would have been versus something with grease."; "I was thinking it would be great for me to start taking photos of my food to remind myself of portions that I'm eating"*). Many participants also described that taking photos changed their eating habits during the study *("I don't think I had seconds at all this week, and part of that is I saw the picture of the first plate. I would snap the picture and put the phone away, but I knew what the photo looked like and I didn't want to take another picture. So that was the deterrent. I don't want to take a picture of another plate."*; *"It limited my snacking. Because I'm a snacker and I was like "no I don't want to take a picture of that granola bar." And it was probably a good thing. I had to either eat the granola bar and take pictures or skip the pictures and likely skip the granola bar. I skipped snacks and seconds.")*. Relatedly, it was fairly common for participants to share positive responses to being asked to take photographs of their food. Many participants commented that taking photos was familiar, for example, *"I liked taking the photos of the food the most just because I'm used it and it was easy."* One participant commented that she enjoyed seeing her food in photos, *"And taking the photographs was actually taking it to the next level. That was* *actually pretty cool. The first day when I took the picture I was like...pshh...look at me. I'm doing it. I got the right food. It's all balanced and it's calorically correct so it gave like instant gratification so I really enjoyed that."*

Participants discussed that familiarity with technology and an interest in health would make people likely to use and benefit from the study app. One participant noted, *"Especially because I already use a smartphone, it was really easy to integrate into everything else I do with my life."* Other participants stated that the app would be well suited for populations interested in health generally (*"There are subpopulations especially in California where you have lots of people interested in health and technology."*) or interest in weight loss (*"for people like me who want to reduce weight."*). They described that logging on study app was convenient or did not requiring much time to complete. As one participant shared, *"For me it's something I carry around all the time. It was just a matter of grabbing it and eating my food so I thought it was pretty convenient."* Participants remarked that they had to modify their clothing or activities when wearing the HR monitor and were also hesitant about being required to wear the HR monitor for a longer period of time. Participants made comments such as, *"I couldn't make it fit up under the clothes so I had to be strategic with it. And in wearing it, it was just too much."* Others expressed reservations about long term use of the HR monitor, *"I just tried to wear it consistently throughout the day so I don't know if I would love that for seven days."*

Many participants shared that they forgot how to operate the study equipment, had a technical problem, and saw age as a possible factor in who might use and benefit from using the study app. Of the participants who shared that they forgot how to use the study equipment properly, several of them spoke about difficulty operating the HR monitor. One participant stated, *"When I was trying to turn it off, the instructions for turning it off, they didn't seem to work so I kept doing it, and kept doing it. I don't know if it died or if I really got it that time, but it was like I pushed it a few times and the light would blink but it wouldn't go off."* Technical problems were also reported by participants. Most comments were similar to this participant who may have accidentally started a questionnaire and was not able to go back, *"for some reason the phone automatically took me back to the beginning of the questions. And I was like why would it do that? So I couldn't figure out how to get back to where I was. It was kinda weird."* Participants also thought age might be a promoting factor (*"The younger adults they wouldn't have a problem with it because they take pictures of everything all the time. It would just be another thing for them to do."*) or limiting factor (*"Like my parents I don't anticipate them really carrying or taking pictures of their food. I don't anticipate this being a natural transition for them."*) in using the study app.

Themes from the second research question. Nearly all participants interviewed were open to proposed clinical applications of the study and expressed either positive expectations or curiosity about the system. A participant open to the study system with positive expectations commented, *"I would like it. It would be really great because I could have that information and be like ok yeah, I need to work on this."* Another participant shared, *"That's really cool. That would be really helpful. One of the things I've realized in food recovery is that for a long time I was unaware of what I was feeling and experiencing. There was a disconnect from my feelings…I was disconnected from my feelings so I overate because I lacked the ability for the little alarm to go off saying* *you're full or is it that I used food to numb out so that I didn't have to feel my feelings. So something like this would be really helpful for times when I am disconnected from what's happening with me and allowing me to tune into oh ok this is what this feels like. I have a tightening in my chest, I'm feeling irritable."* Participants who were open to and curious about using the proposed system often inquired about how the app might learn when to provide alerts and upon what information it would base the alerts. One participant stated, *"I think I'd be curious about how exactly they are getting that info. How does this program know what I'm feeling? Like emotionally or physically? I would ask how it is doing it. Is there some other algorithm?"* Other participants expressed interest in uncovering more information about themselves (*"I guess I would use it to be aware of different things and when I'm stressed out to really think about it. Am I really hungry? Do I really need something or whatever? I think it would make me more conscious of that behavior."*) or conveyed that they would be open to using the system contingent upon it providing helpful information (*"if it helped me achieve my goals that would probably be a good thing."*). Participants stated that alerts from the proposed systems would be helpful in supporting their behavior change. They shared that the alerts also would be helpful in preventing habitual behaviors. One participant said, *"it would stop you right there in your tracks. It would eliminate that whole mindless eating piece so at that point it would have to be a conscious thing. I think that would probably help in terms of losing weight or whatever because then you wouldn't do that kind of thing because you'd be aware of it."* Another participant shared a comparable statement, *"I think it would help halt some of those ingrained behaviors."* Participants often suggested that the system provide a range of coping strategies. One participant asserted she had unique needs for stress reduction strategies, *"I would want to have feedback from the system to get the support. The support I get can't be generic. Because the support for me won't work for case number 14356. I have a unique case number so the support I need would be different."* Another participant proposed a variety of coping strategies she would want, *"Like go watch a video, check your email. It could be like manage your stress or like give you something else to focus on as opposed to your stress, Tetris - games. Like 5 minutes of some non-stressful game. Or minesweeper - I have so many friends that find that very relaxing. Go do a crossword. Sudoku."*

Other themes that were commonly found for the second research question pertained to people with whom they might share information gained from the scenarios, feedback they would like to see about their eating behaviors, and reasons why they might not be interested in the proposed system. Participants frequently reported that they would be interested in sharing information about their connection between stress and eating with people that might help them make behavior change. For example, participants might disclose their tendency to overeat when stressed with a partner or healthcare provider who could support adopting healthy eating habits or managing stress. One participant phrased it like this, *"I'd share it with my partner who I live with and eat with a lot. I'd share it with another woman who I'm close to who works on food issues and weight. I'd share it with my nutritionist and any other medical professional who is working with me on stress."* Another participant remarked, *"I would share it with my husband so he'd be aware of things that were going around. If I were extra stressed and he feels that stress around me to be more supportive of my eating habits and not be (enabling). He's the biggest enabler. I'd tell my closest family, like these are* *the things that are stressful to me. No one has to control my eating but me, but just to not enable it so I think that would be a useful tool."* Participants wanted more detailed feedback on their eating behaviors to assess the variables that influence their eating habits. One participant discussed a desire to see all the collected data, *"Being able to look at cumulative data/photos/history. It would have been helpful for me to be able to look at my week and see my progression. To be trusted to view my own information as a whole."* Relatedly, another described that participants looking for patterns across the data collected might be helpful, *"You could see maybe oh, from 3 to 5, that's when I'm losing it. Yeah I think it could be helpful in tracking if there is any pattern to the chaos. If there is any pattern you can connect with, even if it's just on certain days you notice. Like oh I notice on these days I have this. And it could be you had something out of the ordinary, but it could be oh maybe there are some adjustments you can make on those days. That could be helpful. A graph would be good. I think that the summary is good. The graph is good. And I think at the end of the day and maybe at the end of the week."* Just over two thirds of the sample stated that they would not be interested in using the proposed system, especially in the long term. Limited interested in the long term was one of the concerns expressed, for example, "*I think if I had to do it for a year I would probably get annoyed*." Another participant commented that long term use may not be needed as eating habits might be changed after one year, *"I don't think I would be one that would like it for long term. I think short term for me is good because I feel like I can adjust."*

Participants thought alerts, as part of the proposed system, should be customizable in content and presentation. Some participants desired the ability to snooze or turn off notifications, *"So if I have control to say today I'll listen to the warnings but tomorrow leave me alone. I would like the choice of setting the alerts on or off."* Another participant proposed a generic alert view for privacy, *"Like getting a text from UCSD - some generic way so it doesn't divulge too much."* Participants conveyed that alerts from the proposed system could increase stress if not presented thoughtfully or given in addition to providing an in the moment coping strategy. One participant remarked, *"I think it would add more stress for me personally. It really would, especially if there wasn't an action part. If it was just like "alert!" it's just like somebody running around saying danger all the time. It would be a little stressful."* A similar comment was made by another participant, *"I always found that annoying, but it's also good in that it's letting you know, hey chill out. Or hey, don't eat anymore of this, but to have the alert just randomly pop up. I think that might be kind of annoying."*

Discussion

This project assessed 32 participants with obesity who binge eat to examine the relationship between stress and binge eating in lab and naturalistic settings, integrating EMA of stress and eating behavior with psychophysiological monitoring of stress in the lab. Results indicate that lower ANS flexibility is associated with more severe binge eating behavior, support that self-reported stress captured in a naturalistic setting is linked to increased chance of overeating and having loss of control, and show promise for the potential for future research and clinical applications of systems merging smartphone-based EMA and psychophysiological monitoring.

Eating behaviors and HRV

The pattern of HRV findings across the baseline and stressed conditions suggests the lab stressor induced detectable changes in HRV. The lab stressor lowered ANS flexibility as measured by RMSSD, but not other time domain HRV variables. According to the model of frequency domain HRV variables in which HF power measures parasympathetic tone and LF power measures sympathetic activity, the reductions in HFn and increases in LFn from baseline to stressed segments also provides support that the task induced a detectable stress response. These results are consistent with some prior research (Friederich et al., 2006) and inconsistent with other research (Messerli-Burgy et al., 2010) examining change in HRV through lab stress paradigms in individuals who binge eat. These changes in HRV across the lab protocol may represent a measure of momentary or state ANS flexibility, and this momentary emotion regulation may be important in binge eating behaviors just as it is in substance use behaviors (Thayer et al., 2012). Although more work is needed to provide further evidence and resolve the inconsistencies in the literature, the present findings support that HRV may be a potential state biomarker of increased stress in a population of individuals with obesity who binge eat.

This study found mixed results in determining the links between HRV and binge eating behaviors over the previous four weeks. At baseline, individuals with lower SDNN and lnHF reported more frequent episodes of loss of control, and participants with higher LFn values reported a higher number of overeating episodes. Therefore, lower ANS flexibility, lower parasympathetic activity, and higher sympathetic activity at baseline were associated with increased loss of control and overeating. These findings are in line with our hypothesis and with research demonstrating that resting or trait HRV is related to individual variation in emotion regulation (Appelhans & Luecken, 2006; Thayer et al., 2012). Individuals with lower trait ANS flexibility may have reduced capacity for emotion regulation and may be more prone to engaging in binge eating behaviors in response to stress, which would be expected under the RIM for binge eating. Despite support for the hypothesized connection between low ANS flexibility and overeating and loss of control, a link between ANS flexibility and other aspects of binge eating behaviors (non-nutritious, high calorie foods and breaking dietary rules) was not found. Whereas some baseline HRV variables were associated with binge eating behaviors, measures of HRV during the lab stressor showed no relationships with binge eating behaviors reported over the previous four weeks. Given HRV was substantially changed from baseline to stressed segments of the lab protocol, the associations between HRV measures at these two segments and retrospectively reported binge eating may be expected to be different. However, individual differences in cardiovascular reactivity to stress (i.e., the change in HRV from baseline to stressed to recovery conditions rather than examining HRV from each segment separately) may be important in analyses of ANS flexibility and binge eating behaviors (Friederich et al., 2006).

The present study did not find associations between HRV measured in lab and at-home binge eating behaviors. However, our ability to detect such associations with the at-home data may be limited by the short duration of the EMA at-home period, leading to fewer episodes detected across time, less variability, and possibly low power given our small sample size. The continued logging using the smartphone-based EMA may also have changed participants’ eating, reducing the frequency of binge eating behaviors compared to their retrospective self-report. Future studies may require an extended EMA duration to uncover these associations. A recent EMA study of state ANS flexibility and loss of control in adolescent females did find support for a link between lower momentary HRV and loss of control eating even with a small sample and short at-home period (Ranzenhofer et al., 2016). Alternatively, the EMA data may represent a more accurate account of eating behaviors compared to the retrospectively self-reported episodes assessed over the four weeks prior to the first lab visit. As future research captures ambulatory ANS flexibility, self-reported stress, and eating behaviors, the psychophysiological mechanisms of stress and binge eating can be further studied in a naturalistic environment using more intensive EMA designs.

Based on previous and current findings on the role of ANS flexibility and binge eating, HRV appears to be a promising state marker of stress in this population, and resting HRV may represent trait ANS flexibility, which is related to binge eating behaviors. Under the RIM for binge eating, both trait and state ANS flexibility may be important to understanding and treating binge eating. Trait ANS flexibility provides information on how well individuals regulate emotion and their risk for binge eating generally, whereas state ANS flexibility will allow for determination of how well emotion is currently being regulated and thus the immediate risk for binge eating. Given the varied findings in the literature and in this smaller study, more research is needed to further understand ANS flexibility and binge eating behaviors, examining both state and trait ANS flexibility in lab paradigms and naturalistic assessments of stress and in response to treatment.

Eating behaviors and stress

This study also sought to replicate previous findings of the link between stress and binge eating behaviors using EMA in a naturalistic setting. Findings from the current study support that higher self-reported stress before eating is associated with increased probability of both overeating and loss of control over eating, which is consistent with literature supporting that high negative affect preceded binge eating episodes (Arnow et al., 1992; Haedt-Matt & Keel, 2011b). Our methods allowed for examination of overeating and loss of control separately and supported that stress appeared to have a stronger relationship with overeating than with loss of control in our sample of individual with obesity, half of which met diagnostic criteria for BED. There were no relationships between stress and eating non-nutritious, high calorie foods or reporting breaking of dietary rules. These null results are inconsistent with previous research (Boggiano et al., 2007; Groesz et al., 2012; Torres & Nowson, 2007) and do not fit well within the RIM for binge eating. However, this model may still describe binge eating behaviors with the reflective component encompassing all intentional behavior, not only dietary rules specifically. The finding that breaking dietary rules was not associated with stress fits well with evidence that dietary restraint may not be related to binge eating triggers (Engelberg, Gauvin, & Steiger, 2005). Unfortunately, this study was not able to extend the findings in the literature by only including binge eating behaviors that have been photo-validated as participants only took photos for one day, binge eating behaviors were relatively infrequent during the seven days at-home, and the ratings of photos had some limitations (see section below). Given many participants' willingness to take photos, extending the number of days that photos are taken may allow for photo-validation for future stress-binge eating EMA studies.

Participant experience and feasibility

Adherence is a significant factor to consider with EMA designs. Measures of self-reported and EMA derived adherence in the current study were quite high and similar to rates seen in other EMA studies of binge eating with signal contingent designs (Engelberg et al., 2005; Wegner et al., 2002). Given that after eating and end of the day follow up surveys were more likely to be forgotten than before eating surveys, future studies may want to consider setting reminders or alerts for both surveys. For example, an after eating survey could be automatically prompted within one hour of a before eating survey having been completed. Similarly, the end of the day follow up survey could be set to appear at a participant-specified time before they go to bed. Participants were also compliant with taking photos of their food and many extended the one day requirement to taking pictures on other days. Taking photos of food might be more enjoyable and less burdensome to participants than anticipated and could likely be added to all days of the at-home portion of the study.

Participants found the study system (smartphone, HR monitor, and procedures) to be very user-friendly, were satisfied with instructions and use of the devices, and would use the system for more detailed tracking of the eating. Usability, satisfaction, and comfort ratings for the HR monitor dropped as participants had more experience with the device, suggesting that future studies may need to consider using a different device if they want to capture physiological data for more than one day at home. Using a different HR monitor is also suggested to improve data quality and ensure ambulatory data can be analyzed. Although HRV data quality may have been related to individual factors, not one participant had all segments of at-home data that could be analyzed. Therefore, improvements in ambulatory HRV data quality and processing are needed to advance integration of physiological measures in stress and binge eating EMA research.

During the at-home portion of the study, participants' average frequency of at-home overeating (2.88 episodes per week) and loss of control (1.00 episode per week) were higher than expected, given that only half the sample met diagnostic criteria for BED. The difference between the number of episodes per week as measured by interview versus EMA may reflect underreporting during the interview, increased awareness and accuracy of reports during the at-home portion, or difficulty accurately identifying binge eating behaviors. Examining photos that participants took of their food and the ratings they provided for that eating episode revealed that participants were accurate at detecting when overeating did not happen but were still somewhat liberal in their ratings of overeating, despite substantial in-person training and instructions for at-home use. The photo-validation of overeating is limited by the low frequency of overeating episodes and of photos taken during the at-home portion of the study. For rating non-nutritious foods, participants were better at determining that this behavior did not happen than correctly detecting episodes. Participants were eating some foods that were easily identified as not in the non-nutritious category and but struggled to realize that many foods they were eating were classified as non-nutritious, high calorie foods. Future research may benefit from using a more rigorous, structured classification system for non-nutritious, high calorie foods, such as the Nutrient Rich Foods Index (Drewnowski & Fulgoni, 2014). Overall, longer at-home periods, psychometric evaluations using objective measures, and increased attention to participant training both quantity and quality of foods may be necessary to improve the quality of stress and eating research using EMA.

The semi-structured interview was conducted to obtain qualitative data to answer research questions about participants' experience in the study and their reactions to proposed clinical use of systems that integrate physiological monitoring of stress and eating behaviors. Participants had positive or neutral responses to the study and found the study tasks to be relatively easy. There were elements of the study to which they had negative responses, and they often forgot to complete the after eating questionnaire. To improve completion rates, participants suggested having a home screen to display measures they completed or providing reminder alerts at certain intervals or after completing the first set of measures. Future research may benefit from these changes or from doing a combination of event contingent and signal contingent sampling methods. The HR monitor was perceived as uncomfortable, especially for long term wear, so participants would be hesitant to wear it for a longer period of time and suggested finding another device (e.g., wrist-worn HR monitor). Participants had positive impressions of taking photos of food and many participants reported that answering questions before and after eating allowed them to be more aware of their eating and make positive changes to their eating behaviors. Given the poor quality of the ambulatory HRV data and participants' negative experiences with the HR monitor used in the study, future studies may want to use a more comfortable HR monitor or opt not to use a HR monitor until the HR monitors have improved. Overall, these findings are in line with participants' experiences assessed in the self-reported questionnaires and inform the development of future research using HR monitors for EMA designs of stress and eating.

Participants' reactions to the proposed clinical scenarios were generally positive with many saying that they would be interested in receiving feedback or momentary alerts and interventions using the systems. They often expressed positive expectations that such information or systems would help them build self-knowledge or make changes to their eating. Many participants were curious about how the system might know their levels of stress and were worried that alerts that were too frequent, inaccurate, or indiscrete would be burdensome or ignored. Participants generally preferred not to just receive an alert that they were at risk for unhealthy eating but also to be given a variety of coping strategies that could be personalized so they could receive a momentary intervention that provides the support they need. Participants also wanted more ways to measure their eating and examine factors that might influence their eating behaviors. These systems may need to include customized alerts and interventions, to modify what information is collected over time (i.e., psychophysiological versus contextual versus emotional), and to provide participants a portal or display that allows them to explore their own information. Taken together, their responses will inform the refinement of future systems to study and intervene on stress and eating behaviors.

Clinical applications

Systems that incorporate dietary self-monitoring with EMA with psychophysiological data could be used clinically by integrated them into traditional binge eating treatments or used as standalone interventions with elements of evidence-based treatments. The most studied treatments for binge eating include Interpersonal Therapy, behavioral weight loss, and Cognitive Behavioral Therapy (CBT), which can be done in individual, group, or guided self-help formats (Wilson et al., 2010). CBT for binge eating involves keeping food records with details about the eating context, including emotions, and doing post-binge functional analysis. This functional analysis identifies triggers of binge eating to develop real-time awareness of triggers and urges to binge and inform plans to engage in distraction or an alternative behavior instead of binge eating (Fairburn & Brownell, 2005). Mindfulness-based interventions are growing in both clinical interest and research evidence, and they aim to increase awareness and build acceptance of internal states, such as hunger, satiety, stress, urges to binge, and distressing thoughts through skill building and experiential exercises (Godfrey, Gallo, & Afari, 2015).

A smartphone-based EMA system with psychophysiological monitoring could be incredibly useful for CBT and mindfulness-based interventions for binge eating to improve logging, identification of internal states and triggers, and to plan for and provide alternative behaviors at the right moment. The technology would improve compliance and accuracy of logging as systems could document dates and times of entries and provide reminders for individuals to log if they have not been logging. As used in this study, taking photos of food is a feature that the smartphone-based EMA may compliment traditional logging with text. Individuals found this feature easy and enjoyable to use, and taking and reviewing the photos before eating might provide an opportunity to change food choice and eating behaviors in the moment. Individuals in treatment could use EMA integrated with psychophysiological monitoring to build awareness of their emotions and emotional triggers for eating, possibly overcoming barriers such as low insight or alexithymia. A diverse range of triggers could be examined and tested. These triggers could be personalized to each individual and more sophisticated systems could include data about contextual factors that do not require individuals' input. For example, a log could collect data from the smartphone step counter, GPS signal, proximity to certain people, and information about recent purchases to determine if activity, location, interpersonal context, or purchasing habits are associated with binge eating or other unhealthy eating behaviors. Similar to psychophysiological data, these measures have the benefit of being assessed continuously so they do not rely on individuals, often prone to human error or intervention disengagement, to remember to enter information. Compared to hand written logs, data collected from EMA of individualized triggers and eating behaviors with data visualization and pattern recognition features may make it easier for people to explore and identify their patterns of eating. With or without the help of mental health professionals, these systems could be used to organize and plan for distractions or activities that are available to patients when they are at risk for binge eating. The momentary intervention provided would be significantly better than plans made in traditional therapy settings because they could be initiated without relying on individuals to evaluate or recognize the high risk situation. Additionally, these just-in-time adaptive interventions could reduce barriers to engaging in a coping strategy. For example, coping strategies to call or text a friend, listen to music, watch a funny video, doodle, read a book, or do a relaxation exercise would all be accessible within the same device used to collect data, putting the intervention immediately in the hands of the individual. There are many other advantages of having numerous coping strategies easily accessible, including monitoring treatment engagement, increasing dissemination, and encouraging long term use for maintenance. Individuals' use of coping strategies could be tracked to share with mental health professionals or to determine how often they are using their planned method to avoid binging and how well it worked. These systems could improve access to treatment for binge eating and increase the dissemination of evidence-based interventions. Lastly, the treatment modules could be tailored or staged to match an individual's progress through treatment and provide more infrequent but continued support and intervention throughout a post-treatment maintenance phase, which could sustain intervention effects and prevent relapse. Although more research and development of these systems are needed before they can be used clinically, they offer the promise of substantial enhancements to traditional treatments for binge eating and weight management and may also be considered in the future for use as standalone treatments.

Strengths and limitations

This study has several strengths. Notably, the innovative design integrates naturalistic assessment of eating behaviors with measures of ANS flexibility. The sample of individuals with obesity was comprised of both men and women and a blend of those meeting diagnostic criteria for BED and those who are binge eating at subclinical levels. Thus, external validity and clinical utility might be higher as this sample likely represents a larger clinical spectrum relative to samples of only individuals currently meeting diagnostic criteria for BED. Another unique contribution to the literature is our use of a clinically-relevant population to study the potential development of systems integrating psychophysiology into naturalistic assessment. Results of the qualitative aim provide a much needed user perspective on conducting research and clinical work using portable psychophysiological monitoring. This study provides a critical bridge between theoretical, technical, and clinical paradigms studying stress and eating, serving as the ideal launching point for a new wave of interdisciplinary research to treat binge eating and improve weight management.

There were several limitations of this study. The HR monitor was a common complaint of participants, and the device and associated software also limited HRV analysis with numerous technical problems. Findings may have been impacted by the relatively brief at-home period and participants reporting changes in their eating due to study procedures, which may have lowered the number of binge eating behaviors captured. Similarly, photo-validation of all binge eating episodes was not possible as participants were instructed to take pictures for only one day of the at-home protocol. Collection of stress and eating behaviors via EMA relied on participant prompting and memory. Signal or interval contingent EMA designs might allow for more data to be captured because they signal data collection events independent of participant activity. Further, event contingent designs may not assess adherence as well as designs with system-generated prompts that can analyze how many signaled prompts were completed or ignored. The analysis for Aim 2 may have been underpowered as a power analysis for linear mixed models with dichotomous outcomes was not feasible. Due to a limited sample size, we were not able to determine if the stress-binge eating relationship differs between male and female participants or examine other moderators, such as BED diagnosis. Participant preferences and schedules had some influence on several participants continuing onto the at-home portion of the study. Therefore, full randomization into groups was not possible, possibly introducing bias due to self-selection and availability. The study was also limited in the binge eating behavior items used as they were modified from their original format to adapt to the smartphone-based data collection context. These modified items are of unknown psychometric quality. However, such modifications for use in smartphone- or technology-based research are common and necessary as more research transitions to novel collection media. Further research beyond the scope of this project is needed to develop brief items of binge eating behaviors for mobile data collection and study the psychometric properties of these measures. A final limitation to mention is that there are several potential sources of bias in this study as the researcher (KMG) conducted all the diagnostic interviews, semi-structured interviews, and coded the qualitative data and the photos taken.

Conclusion

Binge eating is a risk factor for weight gain and poor long term weight management but remains poorly understood. Improved theoretical models and innovative tools for assessment and intervention are needed to study and manage triggers for binge eating, such as stress. Measures of ANS flexibility, such as HRV, can provide continuous, objective measures of stress that could initiate interventions before individuals lose control and engage in binge eating. Systems that use EMA with mobile physiological assessment have been designed but never explored within a clinical sample to determine feasibility and clinical utility. This study aimed to better understand the stress and binge eating relationship by examining the relationship between HRV and binge eating behaviors. The link between self-reported stress and binge eating was also analyzed using smartphone-based EMA. To inform future work, the study described the participant experience and determined the feasibility and clinical utility of systems that assess and intervene on binge eating behavior using smartphones and ambulatory physiological measures.

Findings from this study confirm the link between stress and binge eating behaviors and provide promise for future research and clinical applications. Measures of ANS flexibility were associated with more severe binge eating behavior. Consistent with previous research, support was found for an association between stress captured in a naturalistic setting and increased chance of overeating and having loss of control over eating. The study procedures were acceptable to participants who reported enthusiasm for the potential for future research and clinical applications of systems merging smartphone-based EMA and physiological monitoring. These results build the foundation for future work, which will benefit from improved HR monitors, more sophisticated sampling designs and EMA interfaces, increased use of taking photos of food, and longer assessment of at-home binge eating behaviors. Continuing this line of research has the promise of building innovations that detect stress and provide just-in-time interventions when individuals are at risk for binge eating, improving the capacities and reach of evidence-based interventions for eating behaviors and weight management.

Tables

Table 1. Overall study protocol.

Study Visit	**Measures administered**	**Other procedures**	***N***
Phone screen	Eligibility determined through screening measures	Describe study procedures	32
First lab visit	Anthropometric assessment, brief interview to assess binge eating, HRV assessment, self-report measures	Obtain written consent, train to use smartphone app and heart rate monitor, and pay	
At-home day 1	EMA self-report measures		16
At-home day 2			
At-home day 3			
At-home day 4	EMA self-report measures, take photos of food		
At-home day 5	EMA self-report measures		
At-home day 6	EMA self-report measures, wear heart rate monitor		
At-home day 7	EMA self-report measures		
Second lab visit	Self-report measures, semi-structured interview	Obtain equipment, debrief, give payment	

Table 2. Sample demographics.

		Total sample ***N* = 32**
	Age *M* (*SD*)	41 (14.0)
Sex	**Male *n* (%)**	8 (25.0)
	Female *n* (%)	24 (75.0)
Ethnicity	**Hispanic/Latino *n* (%)**	6 (19.4)
	Not Hispanic/Latino *n* (%)	25 (80.6)
Race	**American Indian or Alaska Native *n* (%)**	0 (0)
	Asian *n* (%)	2 (6.3)
	Black or African American *n* (%)	8 (25.0)
	Native Hawaiian or Pacific Islander *n* (%)	0 (0)
	White *n* (%)	14 (43.8)
	Hispanic/Latino *n* (%)	3 (9.4)
	More than one/Mixed *n* (%)	5 (15.6)
Marital status	**Single, never married**	17 (53.1)
	Married	7 (21.9)
	Divorced	2 (6.3)
	Widowed	2 (6.3)
	Separated	0 (0)
	Living with partner	4 (12.5)

Table 3. Sample demographics, continued.

		Total sample ***N* = 32**
Highest level of education	**Less than high school**	0 (0)
	High school graduate/GED	0 (0)
	Some college, no degree	11 (34.4)
	Technical or vocational school graduate	4 (12.5)
	Bachelor's degree	12 (37.5)
	Graduate or professional degree	5 (15.6)
Household income	**<$20,000**	4 (12.5)
	$20,000 – 29,999	5 (15.6)
	$30,000 – 39,999	5 (15.6)
	$40,000 – 49,999	4 (12.5)
	$50,000 – 59,999	4 (12.5)
	$60,000 – 69,999	4 (12.5)
	$70,000 – 79,999	3 (12.5)
	$80,000 or more	3 (12.5)

Table 4. Eating behaviors by diagnostic group and for the total sample.

	Met DSM-5 BED criteria *n* = 15	**Did not meet DSM-5 BED criteria *n* = 17**	**Total sample *N* = 32**
EDE Interview	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**
Overeating episodes	10.40 (6.81)	2.27 (2.28)	6.34 (6.21)
Loss of control episodes	16.27 (10.69)	6.41 (7.69)	11.03 (10.35)
Non-nutritious, high calorie food episodes	32.13 (27.85)	18.20 (13.70)	24.70 (22.30)
Breaking dietary rules episodes	27.13 (31.18)	6.94 (8.48)	16.40 (24.10)
Binge Eating Scale	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**
	24.67 (7.96)	15.82 (5.88)	19.97 (8.16)
Dutch Eating Behaviors Questionnaire	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**
Restrained eating	2.79 (1.40)	2.96 (0.85)	2.88 (0.79)
Emotional eating	3.90 (0.95)	2.91 (1.06)	3.38 (1.11)
Specific emotional eating	3.76 (1.33)	2.88 (1.13)	3.30 (1.16)
Diffuse emotional eating	4.20 (0.83)	2.99 (1.05)	3.55 (1.12)
External eating	3.85 (0.52)	3.39 (0.55)	3.60 (0.58)

Table 5. Frequency of non-nutritious, high calorie foods reported in EDE interview.

Non-nutritious, high calorie foods	**Frequency** ***n* (%)**
Chips (e.g., potato, tortilla, cheetos)	18 (56.25)
Burgers	13 (40.63)
Fries	11 (34.38)
Pizza	10 (31.25)
Soda / energy drinks	10 (31.25)
Fried foods (e.g., fried chicken, fried fish)	9 (28.13)
Mexican (e.g., enchiladas, tortillas, tacos, burritos)	8 (25.00)
Ice cream	8 (25.00)
Fast food	7 (21.88)
Chocolate / candy	7 (21.88)
Hot dog	5 (15.63)
Cake	4 (12.50)
Cookies	3 (9.38)
Chinese food	3 (9.38)
Donuts	2 (6.25)
Pasta	2 (6.25)
Pancakes / waffles	2 (6.25)
Other: Juice, chicken bake, butter, almond butter, honey, pastries, pretzels	Each: 1 (3.13)

Table 6. Frequency of dietary rules in EDE interview.

Dietary Rule	**Frequency** *n* **(%)**
Avoid food type (e.g., no sugary foods, no salt, no fried foods, no processed foods, no meat, no candy, no ice cream)	15 (55.56)
Limits on calories, points, macronutrients	10 (37.04)
Portion control	4 (14.81)
Restrict eating to certain places (e.g., only eat at home)	3 (11.11)
Limit timing of eating (e.g., no snacking between meals, no eating after dinner, no eating in the morning)	3 (11.11)
No soda	2 (7.41)
Increase foods (e.g., more veggies, have a green drink)	2 (7.41)
Other: don't eat today, food substitutions (e.g., veggies instead of cereal), log food, drink water, prepare food ahead of time, don't eat food prepared for other people	Each: 1 (3.70)

Note. Percent values are calculated from participants reported having dietary rules as 5 participants reported only guidelines or that they were not following rules.

Table 7. Summary of data collected during the at-home portion of the study.

	M (*SD*)
Days doing at-home portion	8.75 (4.89)
Full 24 hour days doing at-home portion	7.63 (4.67)
Eating episodes recorded	21.00 (7.97)
Participants' average eating episodes per full day	2.94 (1.17)
Days missed (no recording)	1.31 (5.25)
First questionnaire missed	0.88 (1.09)
Second questionnaire missed	3.06 (2.91)
End of day follow ups completed	6.06 (1.39)
Days of photos taken	3.19 (2.40)
Photos taken	9.06 (7.42)
PSS-4 Total	5.99 (3.18)
Overeating episodes	2.88 (3.18)
Loss of control episodes	1.00 (2.28)
Non-nutritious foods episodes	3.88 (3.93)
Breaking a dietary rule episodes	1.18 (2.23)
Episodes with no overeating, loss of control, non-nutritious foods, or broken dietary rules	11.44 (6.27)

Note. Participants' average eating episodes per full day examined number of eating episodes only on fully days that the participant was doing the at-home portion (i.e., the days they received the smartphone and returned it were half days and were not counted if eating episodes were recorded on those days).

Table 8. Within-participant differences across heart rate variability measures between baseline and serial 7 sections of the lab protocol.

	Baseline *M*, 95% *CI*	**Serial 7 *M*, 95% *CI***	***F***	***p-value***
SDNN	51.64, 41.72-61.56	50.78, 41.83-59.73	0.05	0.82
RMSSD	40.87, 30.72-51.03	32.87, 24.76-40.99	6.99*	0.01
VLF	423.18, 286.61-560.75	526.44, 313.04-739.84	1.24	0.28
LF	738.17, 496.77-979.56	1060.99, 679.29-1442.70	3.61	0.07
HF	1083.41, 497.79-1669.03	599.92, 254.73-945.12	7.13*	0.01
LFn	0.46, 0.38-0.54	0.65, 0.57-0.73	29.88**	<0.001
HFn	0.50, 0.42-0.58	0.27, 0.21-0.32	52.65**	<0.001
LF/HF	1.59, 0.89-2.30	3.35, 2.42-4.27	18.83**	<0.001
HR	69.42, 65.78-73.05	71.00, 65.00-77.00	0.38	0.54

Note. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; ≤ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 9. Correlations among binge eating behaviors from EDE interview.

	Overeating	**Loss of control**	**Non-nutritious, high calorie foods**	**Breaking dietary rules**
Overeating	1	$r = 0.49^{**}$, $p = 0.004$	$r = 0.35$, $p = 0.05$	$r = 0.44^{*}$, $p = 0.01$
Loss of control		1	$r = 0.45^{**}$, $p = 0.008$	$r = 0.32$, $p = 0.07$
Non-nutritious, high calorie foods			1	$r = 0.56^{**}$, $p = 0.001$
Breaking dietary rules				1

Note. Binge eating behaviors are for the previous four weeks. *r* is Pearson's correlation.
$^{*}p < 0.05$ $^{**}p < 0.01$

Table 10. Correlations among heart rate variability measures in the baseline section of the lab protocol.

	SDNN	**RMSSD**	**VLF**	**LF**	**HF**	**LFn**	**HFn**	**LF/HF**	**HR**
SDNN	1	$r=0.84^{**}$, $p<0.001$	$r=0.63^{**}$, $p<0.001$	$r=0.80^{**}$, $p<0.001$	$r=0.76^{**}$, $p<0.001$	$r=-0.14$, $p=0.45$	$r=0.24$, $p=0.21$	$r=-0.04$, $p=0.84$	$r=-.05^{**}$, $p=0.003$
RMSSD		1	$r=0.25$, $p=0.18$	$r=0.54^{**}$, $p=0.002$	$r=0.93^{**}$, $p<0.001$	$r=-0.47^{**}$, $p=0.009$	$r=-0.35$, $p=0.06$	$r=-0.35$, $p=0.06$	$r=-0.54^{**}$, $p=0.002$
VLF			1	$r=0.76^{**}$, $p<0.001$	$r=0.18$, $p=0.34$	$r=0.41^{*}$, $p=0.03$	$r=-0.35$, $p=0.06$	$r=0.59^{**}$, $p=0.001$	$r=-0.17$, $p=0.36$
LF				1	$r=0.45^{*}$, $p=0.01$	$r=0.30$, $p=0.10$	$r=-0.23$, $p=0.23$	$r=0.43^{*}$, $p=0.02$	$r=-0.33$, $p=0.07$
HF					1	$r=-0.46^{*}$, $p=0.01$	$r=0.53^{**}$, $p=0.003$	$r=-0.35$, $p=0.06$	$r=-0.36$, $p=0.05$
LFn						1	$r=-0.96^{**}$ $p<0.001$	$r=0.90^{**}$, $p<0.001$	$r=0.38^{*}$, $p=0.04$
HFn							1	$r=-0.90^{**}$, $p<0.001$	$r=-0.45^{*}$, $p=0.01$
LF/HF								1	$r=0.24$, $p=0.21$
HR									1

Note. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; ≤ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 11. Correlations among heart rate variability measures in the baseline section of the lab protocol and age, BMI, stress, and physical activity levels.

	Age	**BMI**	**PSS-10 Total Score**	**Total MET Minutes per week**
SDNN	$r = -0.32$, $p = 0.10$	$r = -0.31$, $p = 0.10$	$r = -0.26$, $p = 0.18$	$r = 0.21$, $p = 0.29$
RMSSD	$r = -0.35$, $p = 0.06$	$r = -0.25$, $p = 0.18$	$r = -0.30$, $p = 0.12$	$r = 0.06$, $p = 0.76$
VLF	$r = -0.10$, $p = 0.60$	$r = -0.11$, $p = 0.57$	$r = -0.19$, $p = 0.33$	$r = 0.26$, $p = 0.18$
LF	$r = -0.36$, $p = 0.06$	$r = -0.31$, $p = 0.09$	$r = -0.26$, $p = 0.18$	$r = 0.28$, $p = 0.15$
HF	$r = -0.21$, $p = 0.28$	$r = -0.13$, $p = 0.51$	$r = -0.33$, $p = 0.08$	$r = 0.01$, $p = 0.96$
LFn	$r = -0.13$, $p = 0.50$	$r = -0.03$, $p = 0.88$	$r = 0.04$, $p = 0.83$	$r = 0.24$, $p = 0.25$
HFn	$r = 0.06$, $p = 0.77$	$r = 0.01$, $p = 0.98$	$r = 0.04$, $p = 0.86$	$r = -0.15$, $p = 0.45$
LF/HF	$r = -0.06$, $p = 0.77$	$r = -0.11$, $p = 0.57$	$r = -0.13$, $p = 0.52$	$r = 0.27$, $p = 0.16$
HR	$r = 0.02$, $p = 0.91$	$r = 0.53^{**}$, $p = 0.002$	$r = 0.10$, $p = 0.62$	$r = -0.25$, $p = 0.20$

Note. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; $\leq$ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. BMI is body mass index. PSS is the Cohen Perceived Stress Scale. MET is metabolic equivalent task calculated from the International Physical Activity Questionnaire (IPAQ) short form. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 12. Sex differences in heart rate variability measures in the baseline section of the lab protocol.

	Women ***M*, 95% *CI***	**Men** ***M*, 95% *CI***	***F***	***p-value***
SDNN	50.49, 37.79-63.20	57.72, 38.35-77.09	0.52	0.48
RMSSD	42.66, 29.52-55.72	36.66, 16.90-56.42	0.34	0.57
VLF	339.58, 220.50-568.61	698.12, 201.31-1194.94	2.89	0.13
LF	586.27, 354.14-818.39	1287.56, 582.24-1992.88	5.15	0.05
HF	1258.17, 472.57-2043.77	628.84, -7.74-12.65.41	1.88	0.18
LFn	0.39, 0.31-0.47	0.69, 0.50-0.88	11.70*	0.01
HFn	0.56, 0.48-0.64	0.30, 0.11-0.48	10.14*	0.01
LF/HF	0.95, 0.54-1.36	3.76, 1.31-6.20	7.58*	0.03
HR	69.39, 68.16-73.62	69.67, 58.79-80.56	0.003	0.96

Note. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; ≤ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 13. Results of regression models with previous four weeks binge eating behaviors and baseline HRV and HR.

SDNN	***B***	***t***	***p*-value**
Overeating	-1.14	-1.28	0.21
Loss of control	-1.26	-2.26*	0.03
Non-nutritious, high calorie	0.30	1.11	0.28
Breaking dietary rules	-0.05	-0.21	0.84
RMSSD	***B***	***t***	***p*-value**
Overeating	-1.04	-1.50	0.15
Loss of control	-1.14	-0.95	0.06
Non-nutritious, high calorie	0.20	0.70	0.50
Breaking dietary rules	0.04	0.17	0.86
VLF	***B***	***t***	***p*-value**
Overeating	-12.17	-0.94	0.36
Loss of control	-8.87	-1.14	0.28
Non-nutritious, high calorie	2.02	0.51	0.61
Breaking dietary rules	0.66	0.19	0.85
LF	***B***	***t***	***p*-value**
Overeating	-6.88	-0.32	0.75
Loss of control	-20.03	-1.51	0.15
Non-nutritious, high calorie	-1.00	-0.15	0.88
Breaking dietary rules	-0.57	-0.10	0.92
lnHF	***B***	***t***	***p*-value**
Overeating	-0.08	-1.62	0.12
Loss of control	-0.06	-2.21*	0.04
Non-nutritious, high calorie	0.02	1.47	0.16
Breaking dietary rules	-0.01	-0.88	0.40
LFn	***B***	***t***	***p*-value**
Overeating	0.01	2.08*	0.04
Loss of control	0.003	0.62	0.55
Non-nutritious, high calorie	<0.001	-0.11	0.91
Breaking dietary rules	-0.002	-0.86	0.40

Note. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; $\leq$ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. Ln is natural log. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 14. Results of regression models with previous four weeks binge eating behaviors and baseline HRV and HR, continued.

HFn	***B***	***t***	***p*-value**
Overeating	-0.01	-1.71	0.10
Loss of control	-0.005	-1.33	0.20
Non-nutritious, high calorie	0.001	0.71	0.49
Breaking dietary rules	<0.001	0.002	0.90
LF/HF	***B***	***t***	***p*-value**
Overeating	0.06	1.08	0.29
Loss of control	0.01	0.19	0.85
Non-nutritious, high calorie	-0.01	-0.82	0.42
Breaking dietary rules	0.01	0.42	0.68
HR	***B***	***t***	***p*-value**
Overeating	0.33	1.12	0.28
Loss of control	0.19	0.87	0.39
Non-nutritious, high calorie	-0.02	-0.20	0.84
Breaking dietary rules	-0.002	-0.03	0.98

Note. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; $\leq$ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. Ln is natural log. * $p < 0.05$ ** $p < 0.01$

Table 15. Results of regression models with previous four weeks binge eating behaviors and serial 7 HRV and HR.

SDNN	***B***	***t***	***p*-value**
Overeating	-0.80	-0.98	0.34
Loss of control	-0.74	-1.43	0.17
Non-nutritious, high calorie	0.17	0.67	0.51
Breaking dietary rules	-0.14	-0.61	0.55
RMSSD	***B***	***t***	***p*-value**
Overeating	-1.30	-1.76	0.09
Loss of control	-0.71	-1.51	0.14
Non-nutritious, high calorie	0.21	0.91	0.37
Breaking dietary rules	0.16	0.80	0.43
VLF	***B***	***t***	***p*-value**
Overeating	-17.49	-0.81	0.43
Loss of control	-22.85	-1.68	0.11
Non-nutritious, high calorie	5.90	0.87	0.40
Breaking dietary rules	0.58	0.10	0.92
LF	***B***	***t***	***p*-value**
Overeating	-25.50	-0.70	0.49
Loss of control	-40.47	-1.70	0.10
Non-nutritious, high calorie	15.03	1.26	0.22
Breaking dietary rules	-8.79	-0.83	0.41
HF	***B***	***t***	***p*-value**
Overeating	-34.90	-1.03	0.32
Loss of control	-35.91	-1.67	0.11
Non-nutritious, high calorie	9.27	0.86	0.40
Breaking dietary rules	-0.36	-0.04	0.97
LFn	***B***	***t***	***p*-value**
Overeating	0.01	1.90	0.07
Loss of control	-0.002	-0.50	0.62
Non-nutritious, high calorie	<0.01	0.67	0.51
Breaking dietary rules	-0.003	-1.90	0.07

Note. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; ≤ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 16. Results of regression models with previous four weeks binge eating behaviors and serial 7 HRV and HR, continued.

HFn	***B***	***t***	***p*-value**
Overeating	-0.01	-1.54	0.14
Loss of control	<-0.01	-1.31	0.20
Non-nutritious, high calorie	<0.01	0.30	0.77
Breaking dietary rules	<0.01	0.88	0.39
LF/HF	***B***	***t***	***p*-value**
Overeating	0.15	1.60	0.12
Loss of control	0.02	0.32	0.75
Non-nutritious, high calorie	-0.01	-0.50	0.62
Breaking dietary rules	-0.01	-0.53	0.60
HR	***B***	***t***	***p*-value**
Overeating	0.45	1.80	0.09
Loss of control	0.29	1.55	0.14
Non-nutritious, high calorie	-0.07	-0.92	0.37
Breaking dietary rules	-0.07	-0.92	0.37

Note. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; ≤ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. * $p < 0.05$ ** $p < 0.01$

Table 17. Results of regression models with at-home binge eating behaviors and baseline HRV and HR.

SDNN	***B***	***t***	***p*-value**
Overeating	2.84	0.62	0.56
Loss of control	-1.53	-0.21	0.84
Non-nutritious, high calorie	-2.53	-0.74	0.48
Breaking dietary rules	-4.50	-0.82	0.74
RMSSD	***B***	***t***	***p*-value**
Overeating	-1.49	-0.33	0.75
Loss of control	5.22	0.73	0.75
Non-nutritious, high calorie	-5.87	-1.76	0.12
Breaking dietary rules	-7.49	-1.39	0.20
VLF	***B***	***t***	***p*-value**
Overeating	33.29	0.56	0.59
Loss of control	-49.48	-0.52	0.62
Non-nutritious, high calorie	18.82	0.43	0.68
Breaking dietary rules	-25.16	-0.35	0.73
LF	***B***	***t***	***p*-value**
Overeating	26.93	0.23	0.82
Loss of control	-70.10	-0.38	0.72
Non-nutritious, high calorie	-23.13	-0.27	0.80
Breaking dietary rules	-78.20	-0.56	0.59
HF	***B***	***t***	***p*-value**
Overeating	-186.98	-0.66	0.53
Loss of control	345.34	0.77	0.47
Non-nutritious, high calorie	-357.56	-1.71	0.13
Breaking dietary rules	-529.29	-1.57	0.16
LFn	***B***	***t***	***p*-value**
Overeating	>-0.01	-0.14	0.90
Loss of control	-0.01	-0.41	0.69
Non-nutritious, high calorie	0.02	1.50	0.17
Breaking dietary rules	>-0.01	-0.16	0.88

Note. Binge eating behaviors are for the seven day at-home period. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; ≤ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 18. Results of regression models with at-home binge eating behaviors and baseline HRV and HR, continued.

HFn	***B***	***t***	***p*-value**
Overeating	0.004	0.19	0.83
Loss of control	0.01	0.44	0.67
Non-nutritious, high calorie	-0.02	-1.52	0.17
Breaking dietary rules	0.01	0.30	0.78
LF/HF	***B***	***t***	***p*-value**
Overeating	-0.14	-0.66	0.53
Loss of control	-0.07	-0.21	0.84
Non-nutritious, high calorie	0.12	0.78	0.46
Breaking dietary rules	-0.09	-0.36	0.73
HR	***B***	***t***	***p*-value**
Overeating	-2.64	-2.12	0.07
Loss of control	3.00	1.54	0.17
Non-nutritious, high calorie	-1.86	-1.85	0.11
Breaking dietary rules	-2.36	-1.62	0.15

Note. Binge eating behaviors are for the seven day at-home period. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; ≤ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 19. Results of regression models with at-home binge eating behaviors and serial 7 HRV and HR.

SDNN	***B***	***t***	***p*-value**
Overeating	-1.98	-0.46	0.66
Loss of control	3.87	0.56	0.60
Non-nutritious, high calorie	-3.56	-1.02	0.34
Breaking dietary rules	-6.05	-1.09	0.31
RMSSD	***B***	***t***	***p*-value**
Overeating	-2.16	-0.57	0.59
Loss of control	4.18	0.68	0.52
Non-nutritious, high calorie	-4.20	-1.36	0.22
Breaking dietary rules	-6.49	-1.32	0.23
VLF	***B***	***t***	***p*-value**
Overeating	-55.65	-0.59	0.57
Loss of control	64.37	0.42	0.69
Non-nutritious, high calorie	-79.74	-1.03	0.33
Breaking dietary rules	-194.00	-1.58	0.16
LF	***B***	***t***	***p*-value**
Overeating	-190.83	-1.10	0.31
Loss of control	413.11	1.47	0.19
Non-nutritious, high calorie	-249.59	-1.77	0.12
Breaking dietary rules	-454.29	-2.02	0.08
HF	***B***	***t***	***p*-value**
Overeating	-224.95	-1.29	0.24
Loss of control	348.79	1.23	0.26
Non-nutritious, high calorie	-235.64	-1.66	0.14
Breaking dietary rules	-426.85	-1.88	0.10
LFn	***B***	***t***	***p*-value**
Overeating	-0.01	-0.54	0.76
Loss of control	0.03	0.60	0.57
Non-nutritious, high calorie	0.01	0.78	0.79
Breaking dietary rules	0.01	0.13	0.90

Note. Binge eating behaviors are for the seven day at-home period. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; ≤ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 20. Results of regression models with at-home binge eating behaviors and serial 7 HRV and HR, continued.

HFn	***B***	***t***	***p*-value**
Overeating	0.01	0.57	0.59
Loss of control	-0.03	-0.82	0.44
Non-nutritious, high calorie	<0.01	>-0.01	0.99
Breaking dietary rules	<0.01	0.10	0.93
LF/HF	***B***	***t***	***p*-value**
Overeating	-0.40	-1.26	0.25
Loss of control	0.57	1.10	0.31
Non-nutritious, high calorie	0.06	0.23	0.83
Breaking dietary rules	-0.13	-0.30	0.77
HR	***B***	***t***	***p*-value**
Overeating	-1.93	-1.53	0.18
Loss of control	2.78	1.39	0.21
Non-nutritious, high calorie	-1.36	-1.18	0.28
Breaking dietary rules	2.38	-1.48	0.19

Note. Binge eating behaviors are for the seven day at-home period. SDNN is standard deviation of normal-to-normal (NN) interval in ms. RMSSD is root mean square of successive differences between NN intervals in ms. VLF is very low frequency range (VLF; $\leq$ 0.04 Hz) in ms^2/Hz. LF is low frequency range (LF; 0.04-0.15 Hz) ms^2. HF is high frequency range (HF; 0.15-0.4 Hz) ms^2/Hz. LFn is the low frequency norm value, which minimizes the effect of changes in the very low frequency power in nu. HFn is the high frequency norm value in nu, which minimizes the effect of changes in the very low frequency power. LF/HF is the LF/HF ratio. HR is heart rate in bpm. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 21. Correlations among at-home binge eating variables and scores on the PHQ-9, GAD-7, PCL-C, smartphone attitudes, and smartphone self-efficacy scales.

	Overeating	**Loss of control**	**Non-nutritious, high calorie**	**Breaking dietary rules**
PHQ-9	$r = -0.08$, $p = 0.78$	$r = 0.44$, $p = 0.09$	$r = 0.32$, $p = 0.23$	$r = 0.35$, $p = 0.18$
GAD-7	$r = 0.16$, $p = 0.55$	$r = 0.64^{**}$, $p < 0.01$	$r = 0.24$, $p = 0.37$	$r = 0.05$, $p = 0.86$
PCL-C	$r = 0.11$, $p = 0.68$	$r = 0.51^{*}$, $p = 0.04$	$r = 0.08$, $p = 0.77$	$r = 0.05$, $p = 0.84$
Worst pain severity	$r = 0.49$, $p = 0.06$	$r = 0.13$, $p = 0.64$	$r = 0.17$, $p = 0.53$	$r = -0.09$, $p = 0.74$
Average pain severity	$r = 0.20$, $p = 0.47$	$r = 0.02$, $p = 0.93$	$r = 0.25$, $p = 0.35$	$r = 0.03$, $p = 0.91$
Pain interference	$r = 0.23$, $p = 0.39$	$r = 0.37$, $p = 0.16$	$r = 0.35$, $p = 0.18$	$r = -0.13$, $p = 0.64$
Smartphone attitudes	$r = -0.06$, $p = 0.82$	$r = -0.01$, $p = 0.97$	$r = -0.04$, $p = 0.89$	$r = -0.06$, $p = 0.82$
Smartphone self-efficacy	$r = -0.03$, $p = 0.92$	$r = -0.23$, $p = 0.41$	$r = -0.11$, $p = 0.68$	$r = -0.23$, $p = 0.39$

Note. PHQ-9 is the Patient Health Questionnaire. GAD-7 is the Generalized Anxiety Disorder scale. PCL-C is the PTSD Checklist Civilian Version. Worst pain severity, average pain severity, and pain interference are items from the Brief Pain Inventory assessing past 24 hour pain. Smartphone attitudes is the modified Computer Attitudes Scale. Smartphone self-efficacy is the Computer Self-Efficacy Scale. $^{*}p < 0.05$ $^{**}p < 0.01$

Table 22. Sex differences at-home binge eating measures.

	Women ***M*, 95% *CI***	**Men** ***M*, 95% *CI***	***F***	***p-value***
Overeating	2.75, 1.17-4.33	3.25, -5.11-11.61	0.07	0.80
Loss of control	0.83, -0.52-2.18	1.50, -3.27-6.27	0.24	0.63
Non-nutritious, high calorie	4.25, 1.43-7.07	2.75, 0.03-5.47	0.42	0.53
Breaking dietary rules	2.17, 0.54-3.79	0.75, -0.77-2.27	1.13	0.31

$^{*}p < 0.05$ $^{**}p < 0.01$

Table 23. Parameter estimates of the multilevel model of overeating as a function of self-reported stress during the seven day at-home period.

Fixed effects	**Estimate**	**SE**	***t***	***p-value***	$e^{estimate}$	**95% *CI* for** $e^{estimate}$
Intercept	-2.21	0.40	-5.58**	<0.01	0.11	0.05-0.24
PSS_Tcw	0.17	0.07	2.56*	0.01	1.189	1.04-1.36
PSS_Tcb	-0.20	0.07	-2.75*	0.01	0.82	0.71-0.95
Hourc	<0.01	<0.01	1.12	0.27	1.00	1.00-1.01
Random effects	**Estimate**	**SE**	***z***	***p-value***		**95% *CI* for estimate**
Residual	0.75	0.07	11.59**	<0.01		0.64-0.89
Autocorrelation	0.01	0.12	0.11	0.92		-0.21-0.24

Note. *N* = 16. 340 observations total. Degrees of freedom were conservatively calculated based on the total number of participants, not on the number of observations. PSS_Tcw is the PSS-4 total score grand mean centered within person variable. PSS_Tcb is the PSS-4 total score grand mean centered between person variable. Hourc is the hour into the seven day at-home period grand mean centered.

$^{*}p < 0.05$ $^{**}p < 0.01$

Table 24. Parameter estimates of the multilevel model of loss of control as a function of self-reported stress during the seven day at-home period, including anxiety and PTSD symptoms as covariates.

Fixed effects	**Estimate**	**SE**	***t***	***p*-value**	**$e^{estimate}$**	**95% *CI* for $e^{estimate}$**
Intercept	-8.10	2.36	-3.43*	<0.01	<0.01	<0.01-0.03
PSS_Tcw	0.37	0.08	4.531**	<0.0	1.45	1.23-1.70
PSS_Tcb	-0.40	0.68	-0.59	0.56	0.67	0.17-2.56
Hourc	-0.01	<0.01	-3.71**	<0.01	0.99	0.98-1.00
GAD-7c	1.08	0.73	1.49	0.14	2.94	0.70-12.28
PCL-Cc	0.02	0.19	0.12	0.91	1.02	0.70-1.49
Random effects	**Estimate**	**SE**	***z***	***p*-value**		**95% *CI* for estimate**
Residual	0.26	0.02	11.65**	<0.01		0.22-0.31
Autocorrelation	0.24	0.10	2.37*	0.02		0.03-0.42

Note. *N* = 16. 340 observations total. Degrees of freedom were conservatively calculated based on the total number of participants, not on the number of observations. PSS_Tcw is the PSS-4 total score grand mean centered within person variable. PSS_Tcb is the PSS-4 total score grand mean centered between person variable. Hourc is the hour into the seven day at-home period grand mean centered. GAD-7c is the Generalized Anxiety Disorder scale total score centered on the grand mean. PCL-Cc is the PTSD Checklist civilian version total score centered on the grand mean.

$^{*}p < 0.05$ $^{**}p < 0.01$

Table 25. Parameter estimates of the multilevel model of loss of control as a function of self-reported stress during the seven day at-home period.

Fixed effects	**Estimate**	**SE**	***t***	***p-value***	$e^{estimate}$	**95% *CI* for** $e^{estimate}$
Intercept	-5.93	1.07	-5.53**	<0.01	<0.01	<0.01-0.02
PSS_Tcw	0.33	0.08	4.37**	<0.01	1.45	1.20-1.62
PSS_Tcb	-0.37	0.08	-4.55**	<0.01	0.69	0.59-0.81
Hourc	-0.01	<0.01	-3.71**	<0.01	0.99	0.98-1.00
Random effects	**Estimate**	**SE**	***z***	***p-value***		**95% *CI* for estimate**
Residual	0.25	0.02	11.71**	<0.01		0.21-.0.30
Autocorrelation	0.26	0.10	2.60*	0.01		0.06-0.44

Note. *N* = 16. 340 observations total. Degrees of freedom were conservatively calculated based on the total number of participants, not on the number of observations. PSS_Tcw is the PSS-4 total score grand mean centered within person variable. PSS_Tcb is the PSS-4 total score grand mean centered between person variable. Hourc is the hour into the seven day at-home period grand mean centered.

$^{*}p < 0.05$ $^{**}p < 0.01$

Table 26. Parameter estimates of fixed effects of the multilevel model of non-nutritious, high calorie foods as a function of self-reported stress during the seven day at-home period.

Fixed effects	**Estimate**	**SE**	***t***	***p*-value**	**$e^{estimate}$**	**95% *CI* for $e^{estimate}$**
Intercept	-1.40	0.34	-4.13**	<0.01	0.25	0.13-0.48
PSS_Tcw	0.11	0.06	1.64	0.10	1.11	0.97-1.26
PSS_Tcb	-0.11	0.07	-1.74	0.08	0.89	0.79-1.02
Hourc	<0.01	<0.01	0.80	0.43	1.00	1.00-1.01
Random effects	**Estimate**	**SE**	***z***	***p*-value**		**95% *CI* for estimate**
Residual	0.90	0.08	11.53**	<0.01		0.75-1.05
Autocorrelation	-0.01	0.18	-0.06	0.96		-0.36-0.34

Note. *N* = 16, 340 observations. Degrees of freedom were conservatively calculated based on the total number of participants, not on the number of observations. PSS_Tcw is the PSS-4 total score grand mean centered within person variable. PSS_Tcb is the PSS-4 total score grand mean centered between person variable. Hourc is the hour into the seven day at-home period grand mean centered.

$^{*}p < 0.05$ $^{**}p < 0.01$

Table 27. Parameter estimates of fixed effects of the multilevel model of breaking dietary rules as a function of self-reported stress during the seven day at-home period.

Fixed effects	**Estimate**	**SE**	***t***	***p-value***	**$e^{estimate}$**	**95% *CI* for $e^{estimate}$**
Intercept	-2.59	0.43	-6.07**	<0.01	0.08	0.03-0.17
PSS_Tcw	0.12	0.07	1.69	0.09	1.13	0.98-1.31
PSS_Tcb	-1.15	0.08	-1.95	0.05	0.86	0.74-1.00
Hourc	<-0.01	<0.01	-0.21	0.84	1.00	0.99-1.01
Random effects	**Estimate**	**SE**	***z***	***p-value***		**95% *CI* for estimate**
Residual	0.64	0.06	11.58**	<0.01		0.54-0.76
Autocorrelation	0.05	0.28	0.20	0.85		-0.45-0.53

Note. *N* = 16. 340 observations total. Degrees of freedom were conservatively calculated based on the total number of participants, not on the number of observations. PSS_Tcw is the PSS-4 total score grand mean centered within person variable. PSS_Tcb is the PSS-4 total score grand mean centered between person variable. Hourc is the hour into the seven day at-home period grand mean centered.

$^{*}p < 0.05$ $^{**}p < 0.01$

Figures

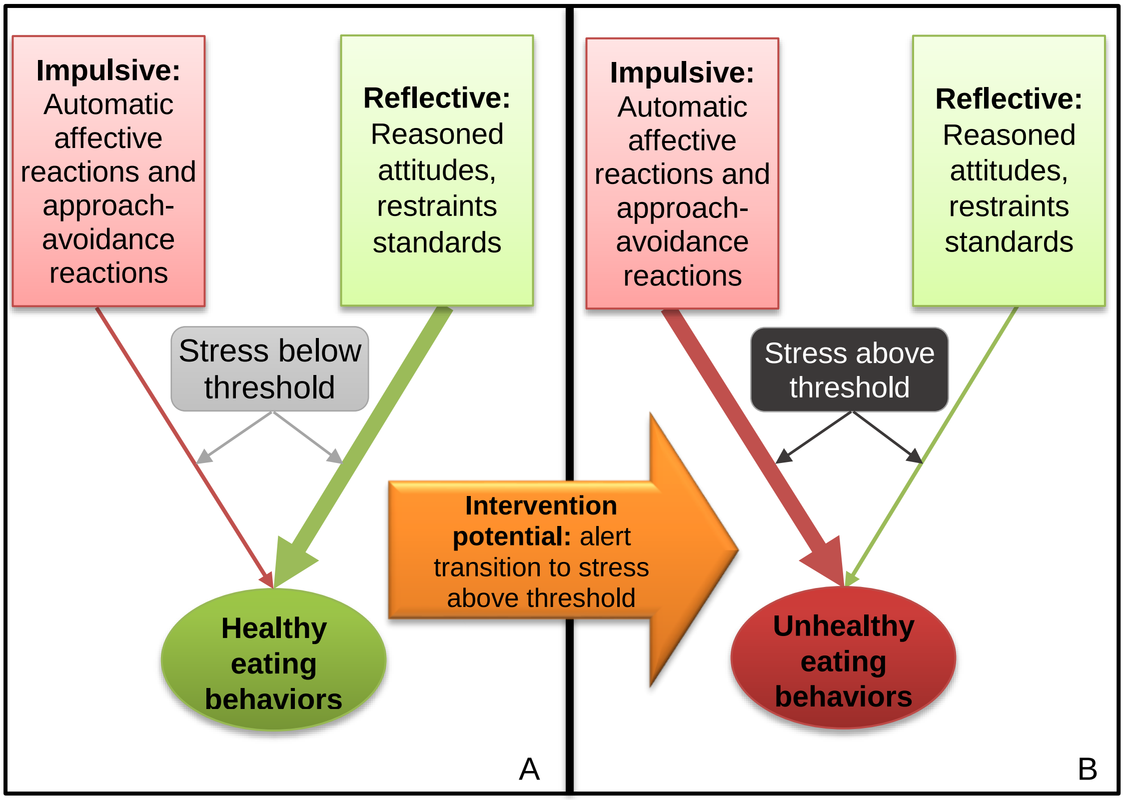
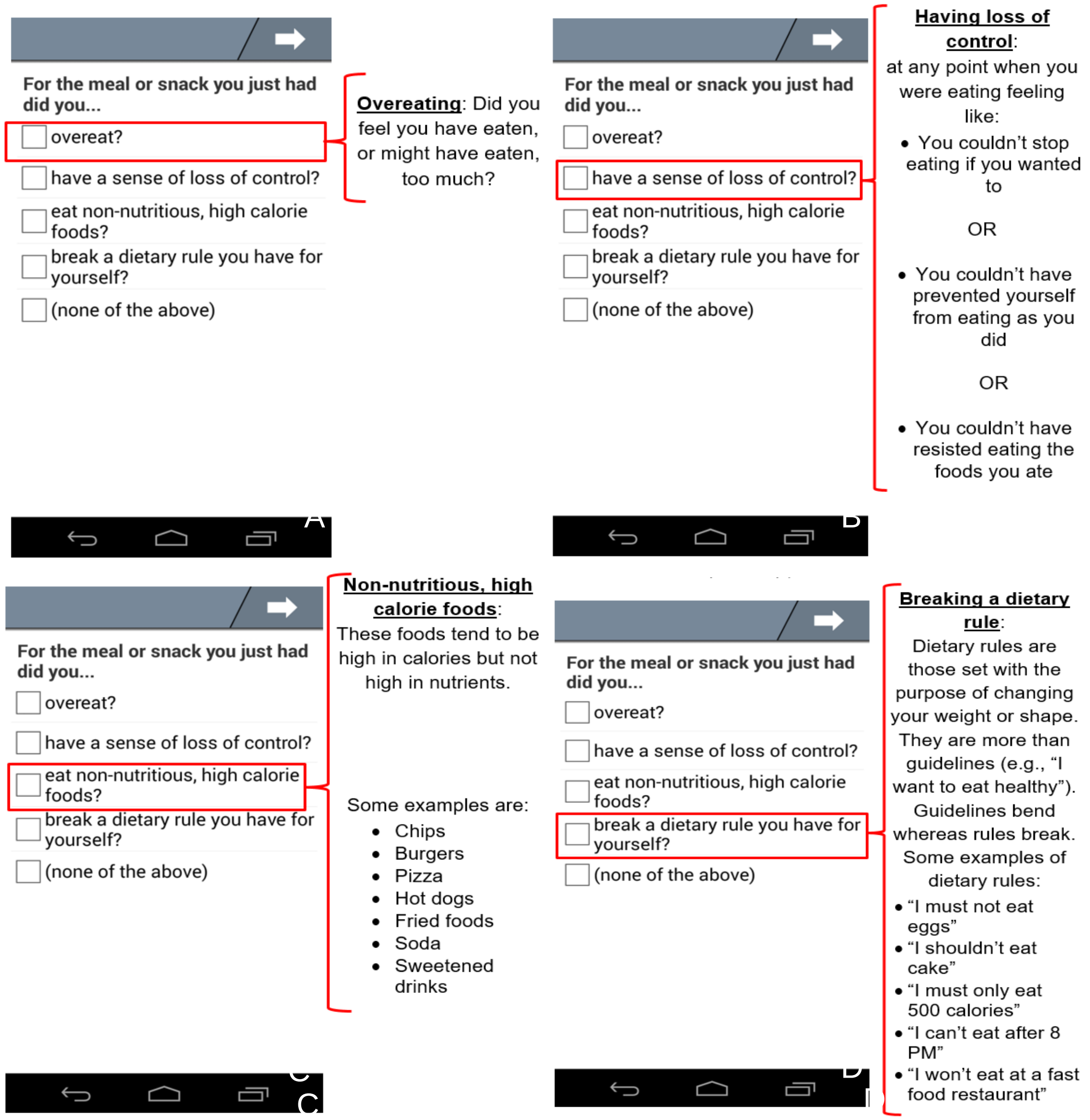


Figure 1. The Reflective Impulsive Model for unhealthy eating when an individual's stress threshold is not surpassed (A) and surpassed (B). The orange arrow represents the intervention potential within to this model.



For the meal or snack you just had did you...

☐ overeat?
☐ have a sense of loss of control?
☐ eat non-nutritious, high calorie foods?
☐ break a dietary rule you have for yourself?
☐ (none of the above)

Overeating: Did you feel you have eaten, or might have eaten, too much?

For the meal or snack you just had did you...

☐ overeat?
☐ have a sense of loss of control?
☐ eat non-nutritious, high calorie foods?
☐ break a dietary rule you have for yourself?
☐ (none of the above)

Having loss of control: at any point when you were eating feeling like:

- You couldn't stop eating if you wanted to

OR

- You couldn't have prevented yourself from eating as you did

OR

- You couldn't have resisted eating the foods you ate

For the meal or snack you just had did you...

☐ overeat?
☐ have a sense of loss of control?
☐ eat non-nutritious, high calorie foods?
☐ break a dietary rule you have for yourself?
☐ (none of the above)

Non-nutritious, high calorie foods: These foods tend to be high in calories but not high in nutrients.

Some examples are:

- Chips
- Burgers
- Pizza
- Hot dogs
- Fried foods
- Soda
- Sweetened drinks

For the meal or snack you just had did you...

☐ overeat?
☐ have a sense of loss of control?
☐ eat non-nutritious, high calorie foods?
☐ break a dietary rule you have for yourself?
☐ (none of the above)

Breaking a dietary rule: Dietary rules are those set with the purpose of changing your weight or shape. They are more than guidelines (e.g., "I want to eat healthy"). Guidelines bend whereas rules break. Some examples of dietary rules:

- "I must not eat eggs"
- "I shouldn't eat cake"
- "I must only eat 500 calories"
- "I can't eat after 8 PM"
- "I won't eat at a fast food restaurant"

Figure 2 Participant training materials for rating eating behavior items. Overeating (A); loss of control (B); non-nutritious, high calorie foods (C); breaking dietary rules (D).

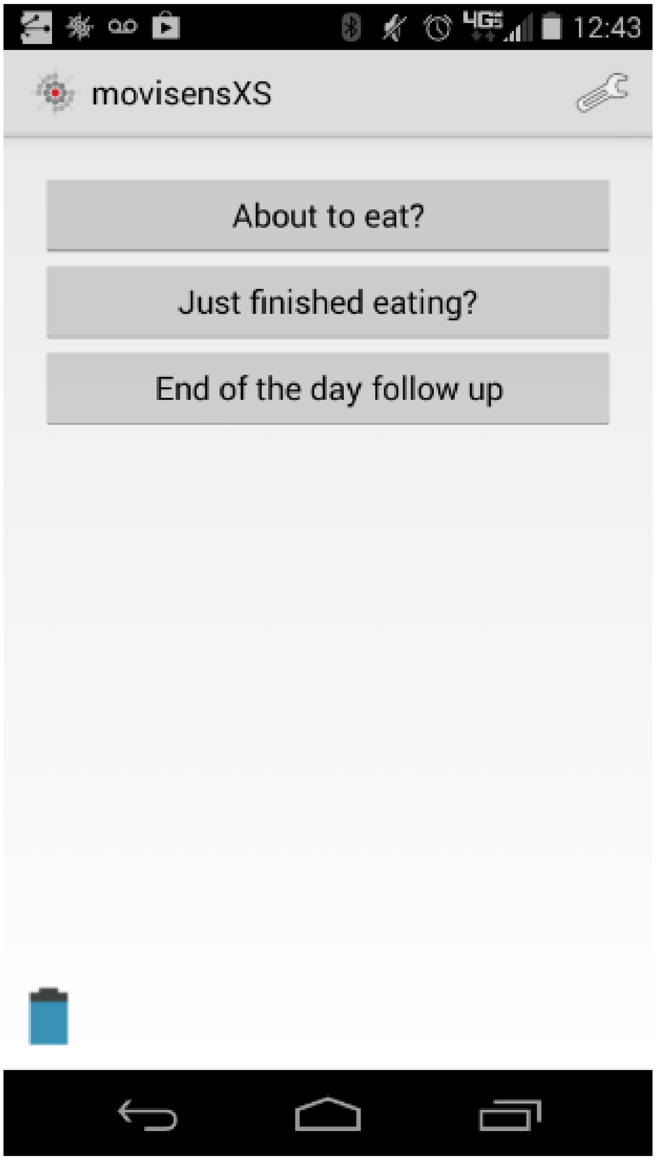
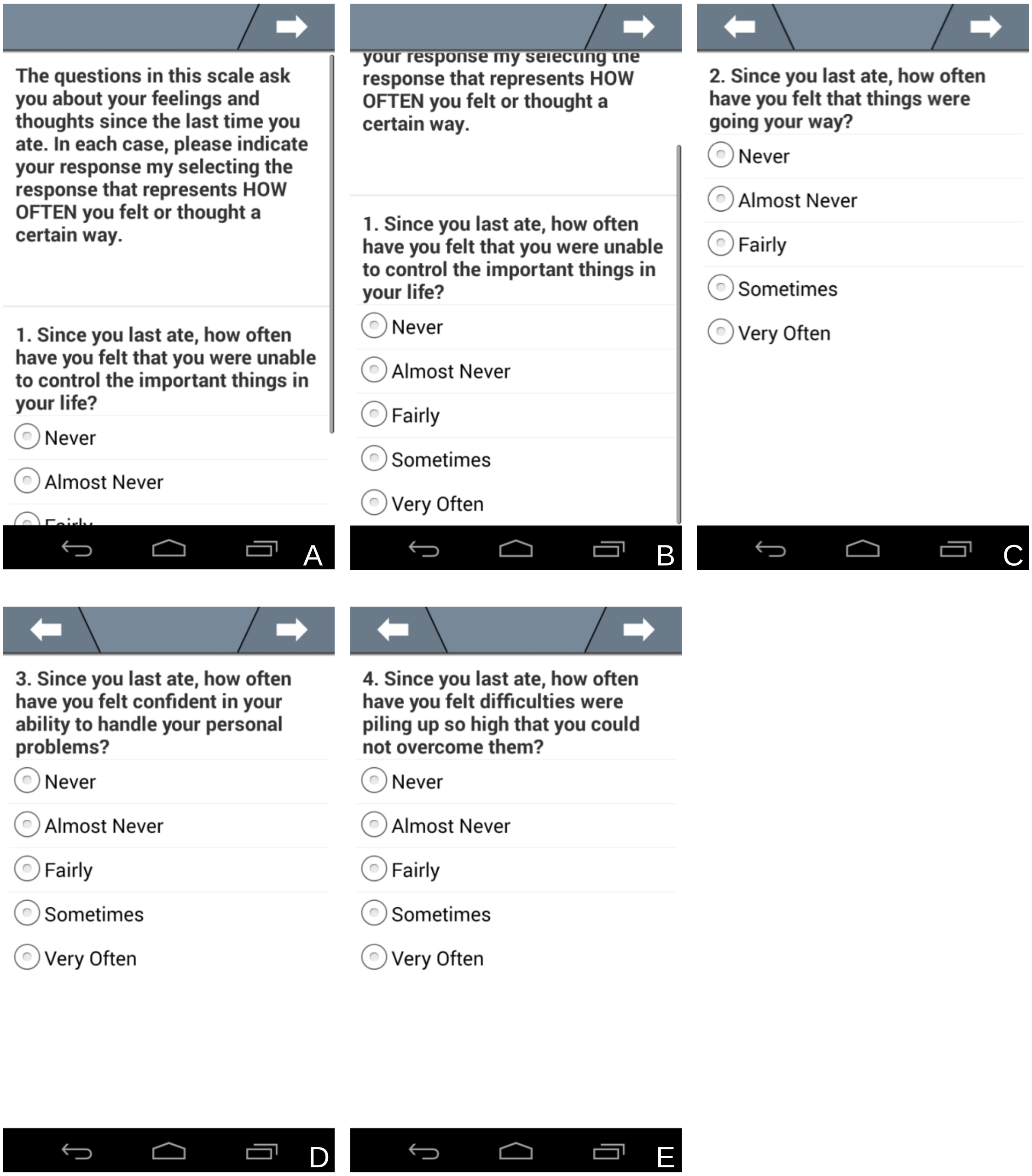


Figure 3. Home screen of smartphone-based EMA data collection.



The questions in this scale ask you about your feelings and thoughts since the last time you ate. In each case, please indicate your response my selecting the response that represents HOW OFTEN you felt or thought a certain way.

1. Since you last ate, how often have you felt that you were unable to control the important things in your life?

○ Never

○ Almost Never

○ Fairly

your response my selecting the response that represents HOW OFTEN you felt or thought a certain way.

1. Since you last ate, how often have you felt that you were unable to control the important things in your life?

○ Never

○ Almost Never

○ Fairly

○ Sometimes

○ Very Often

2. Since you last ate, how often have you felt that things were going your way?

○ Never

○ Almost Never

○ Fairly

○ Sometimes

○ Very Often

3. Since you last ate, how often have you felt confident in your ability to handle your personal problems?

○ Never

○ Almost Never

○ Fairly

○ Sometimes

○ Very Often

4. Since you last ate, how often have you felt difficulties were piling up so high that you could not overcome them?

○ Never

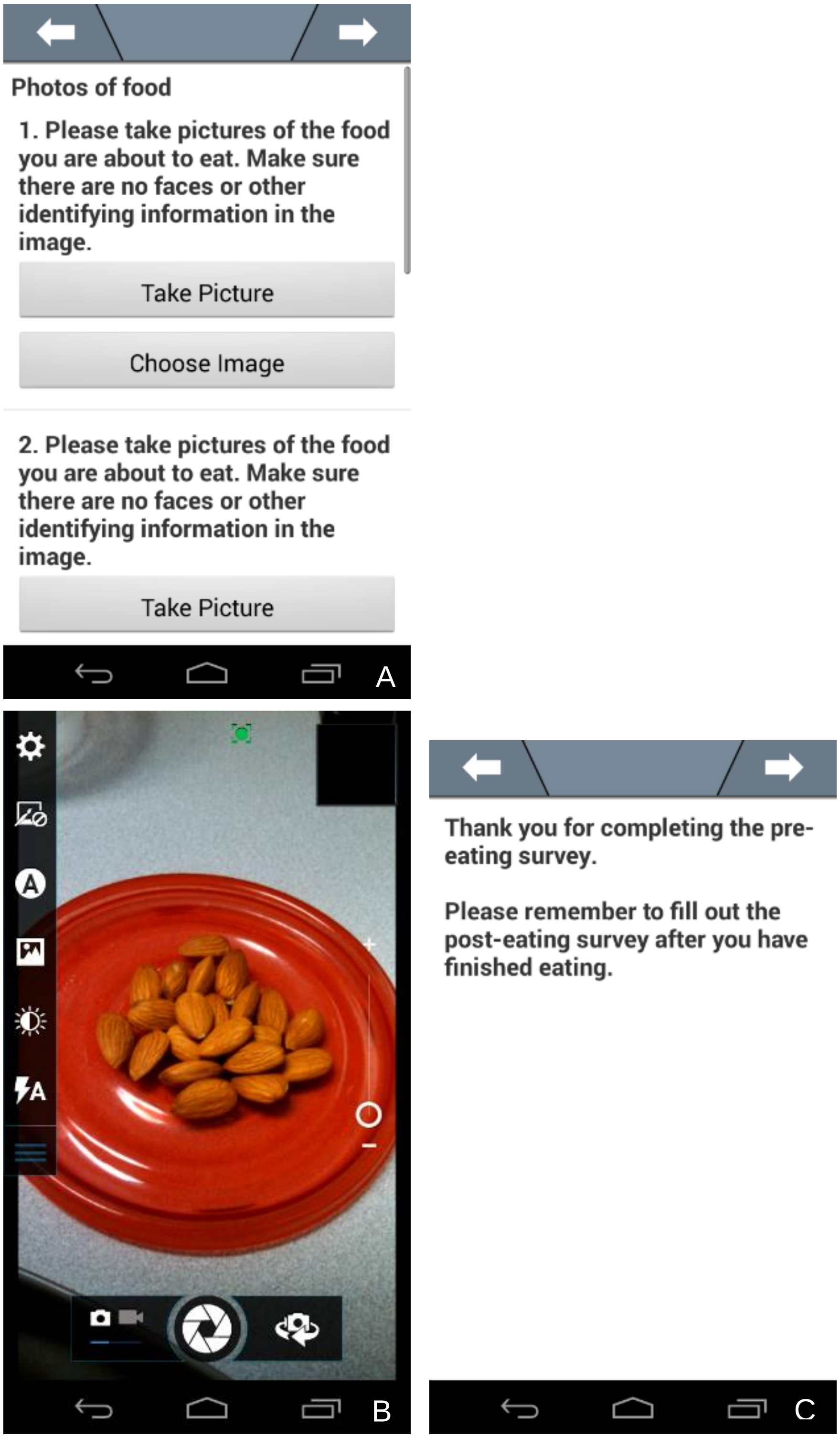
○ Almost Never

○ Fairly

○ Sometimes

○ Very Often

Figure 4 Screenshots of smartphone-based data collection. Cohen’s PSS 4-item version presented after participants select the “about to eat?” button on the home screen. Instructions (A); item 1 (B); item 2 (C); item 3 (D); item 4 (E).



Photos of food

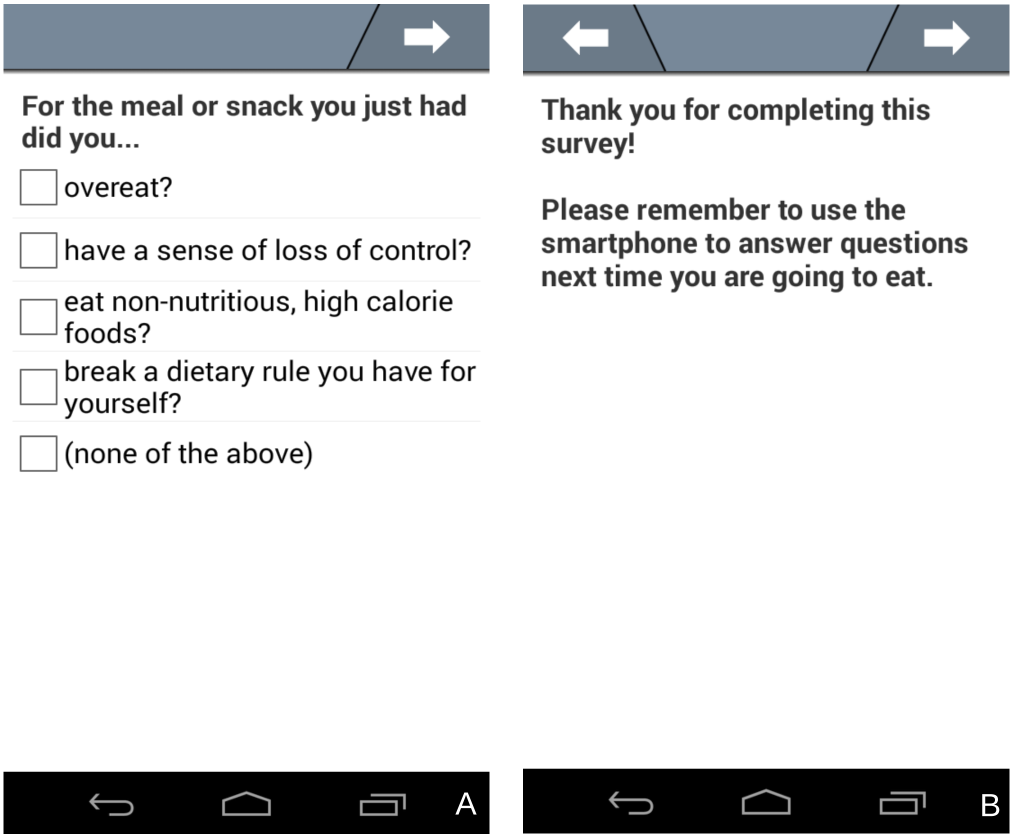
1. Please take pictures of the food you are about to eat. Make sure there are no faces or other identifying information in the image.

2. Please take pictures of the food you are about to eat. Make sure there are no faces or other identifying information in the image.

Thank you for completing the pre-eating survey.

Please remember to fill out the post-eating survey after you have finished eating.

Figure 5.. Screenshots of smartphone-based data collection. Photos of food about to be consumed (A-B); reminder to complete post-eating questions (C).



For the meal or snack you just had did you...

☐ overeat?

☐ have a sense of loss of control?

☐ eat non-nutritious, high calorie foods?

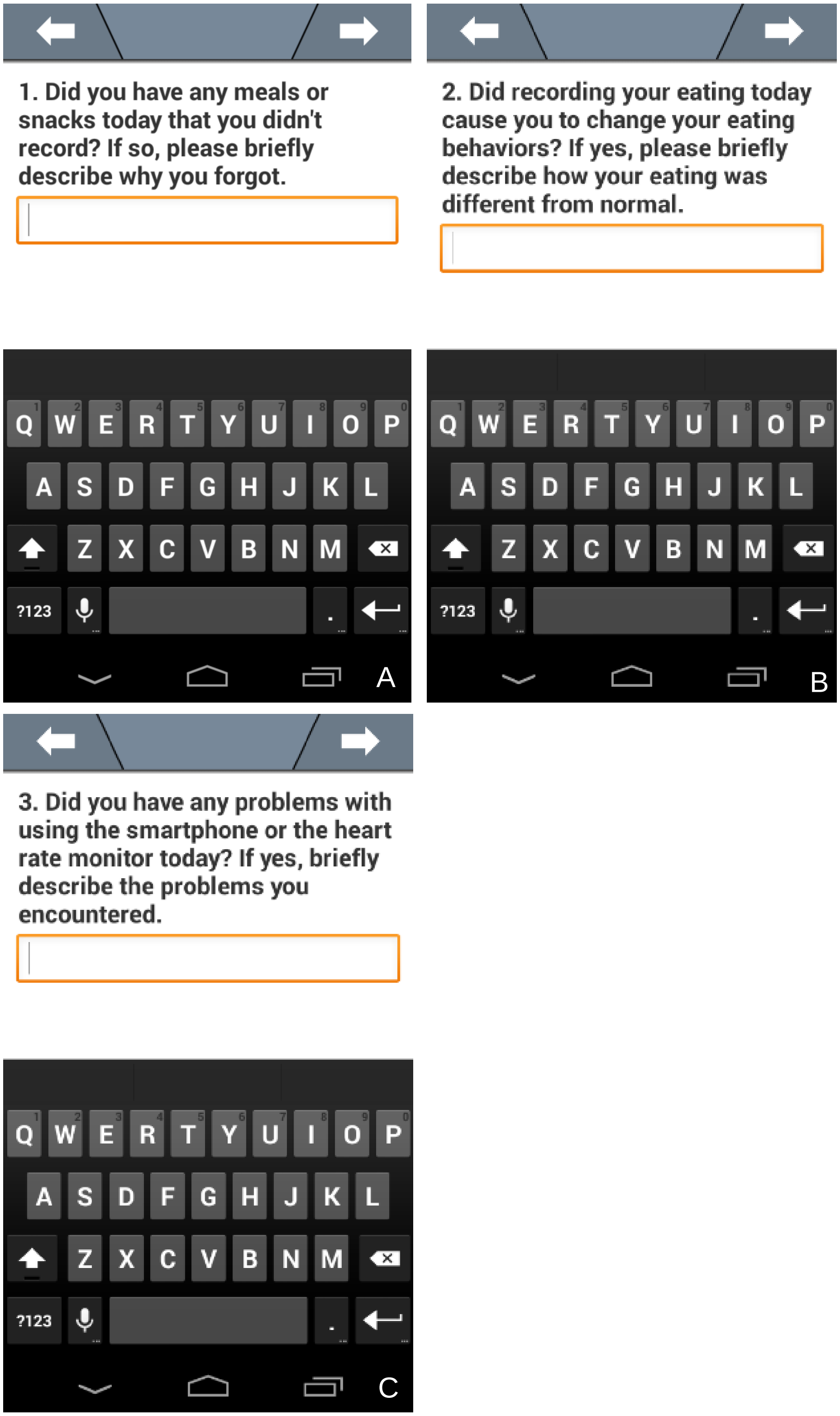
☐ break a dietary rule you have for yourself?

☐ (none of the above)

Thank you for completing this survey!

Please remember to use the smartphone to answer questions next time you are going to eat.

Figure 6. Screenshots of smartphone-based data collection. Eating behaviors (A); reminder to complete future measures (B).



1. Did you have any meals or snacks today that you didn't record? If so, please briefly describe why you forgot.

2. Did recording your eating today cause you to change your eating behaviors? If yes, please briefly describe how your eating was different from normal.

3. Did you have any problems with using the smartphone or the heart rate monitor today? If yes, briefly describe the problems you encountered.

Figure 7. Screenshots of smartphone-based data collection. End of the day follow up questions.

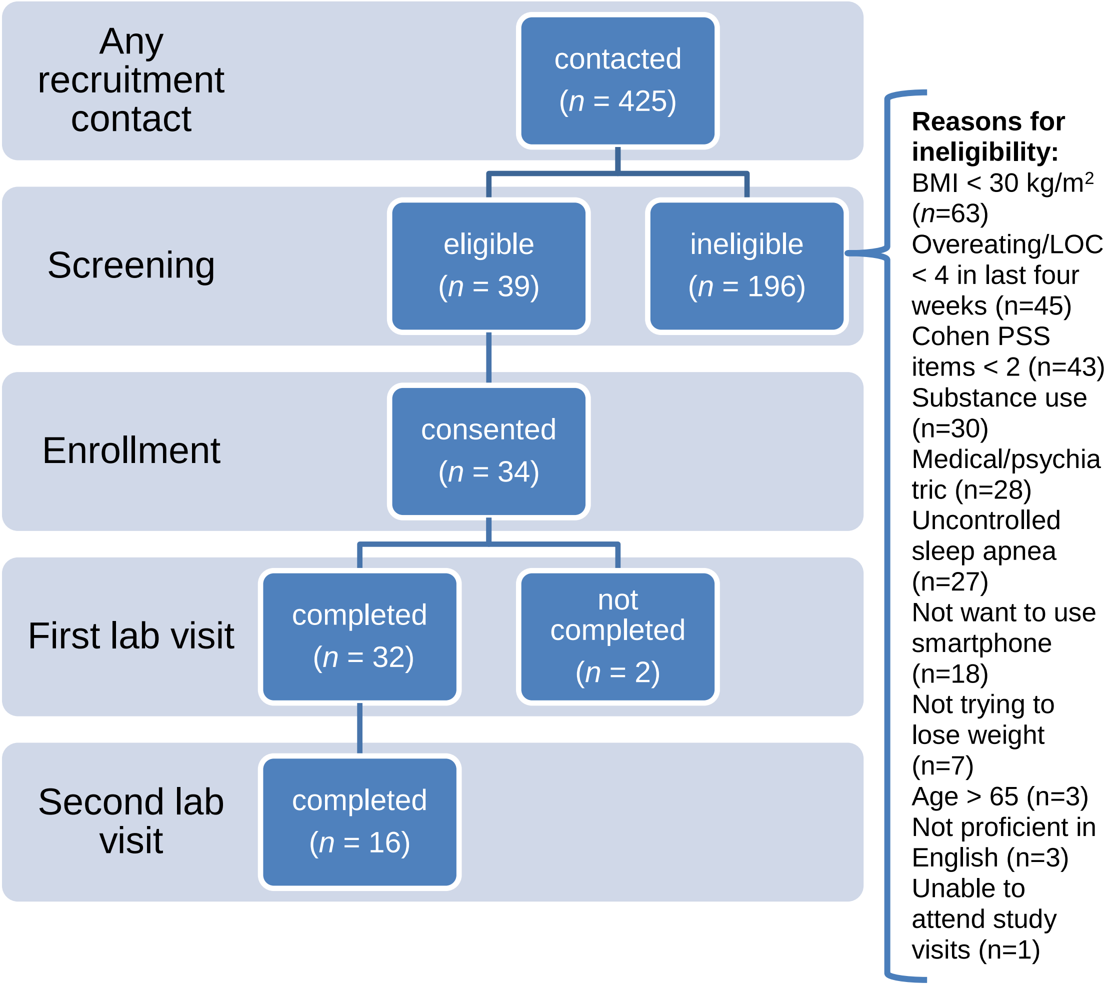


Figure 8. Flow chart of recruitment and study participation.

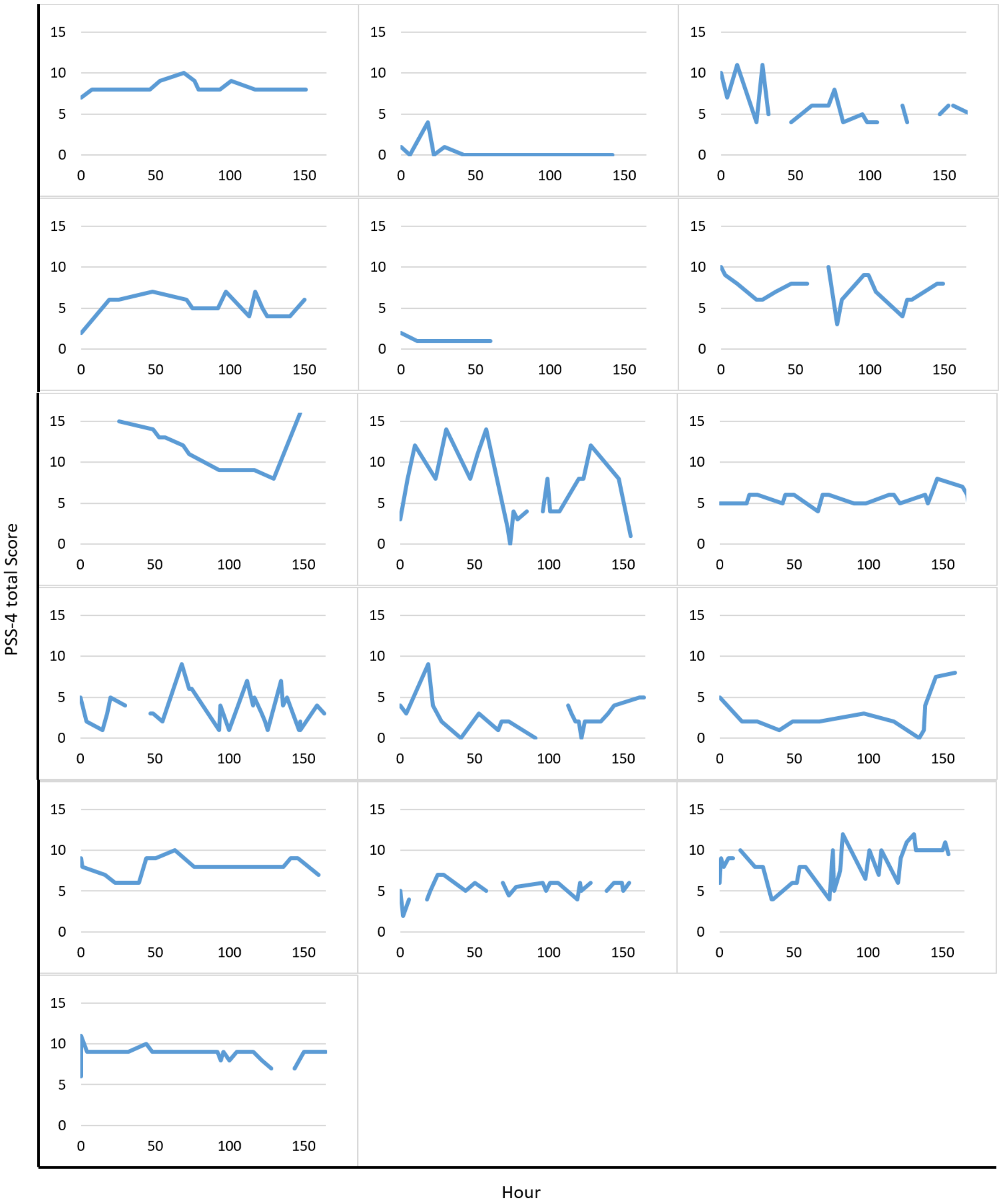


Figure 9. Panel plots of self-reported stress for each participant across the seven day at-home portion of the study.

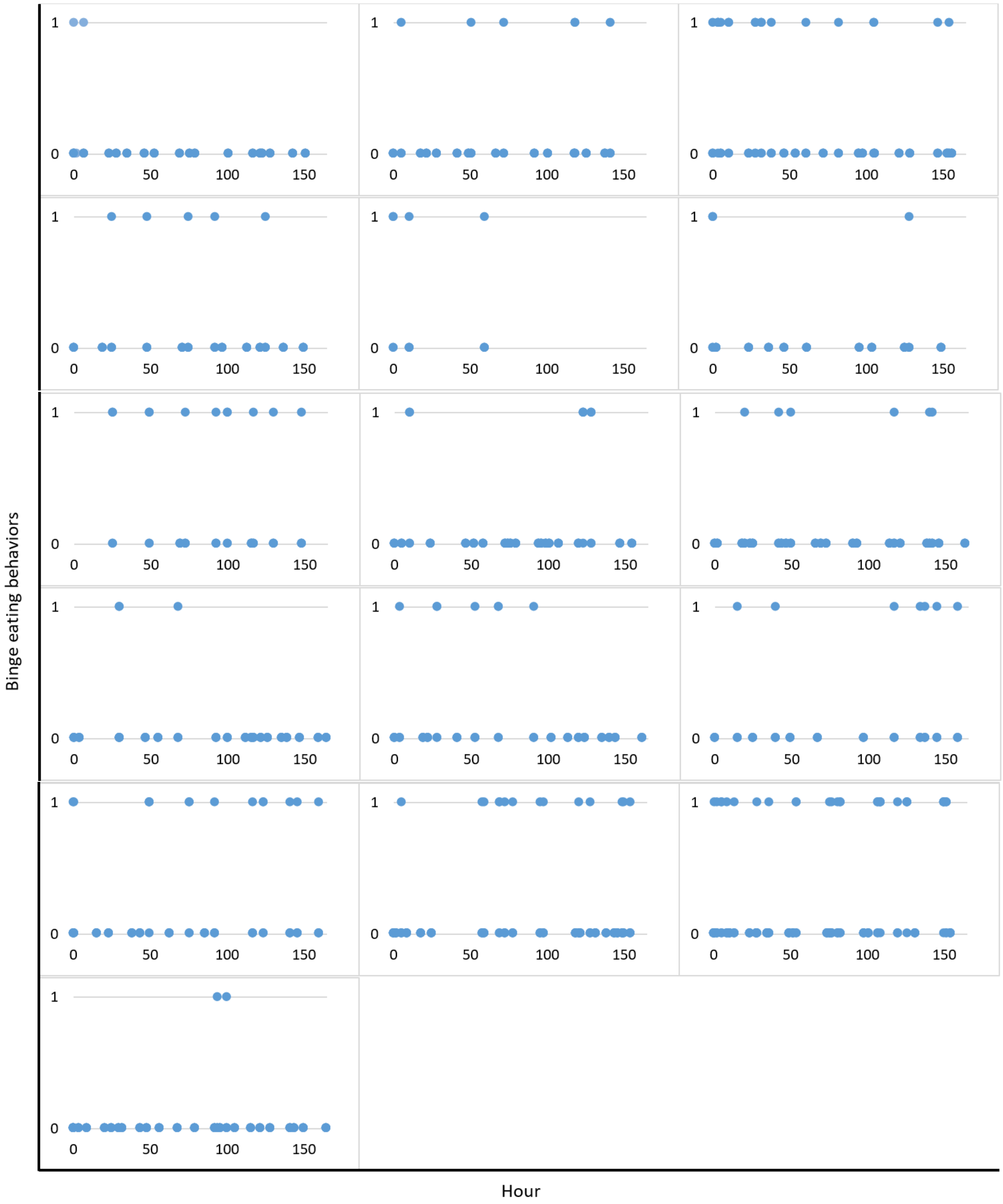


Figure 10. Panel plots of self-reported eating behaviors for each participant across the seven day at-home portion of the study.

Note. “0” corresponds to absence of binge eating behavior, and “1” corresponds to the presence of a binge eating behavior.

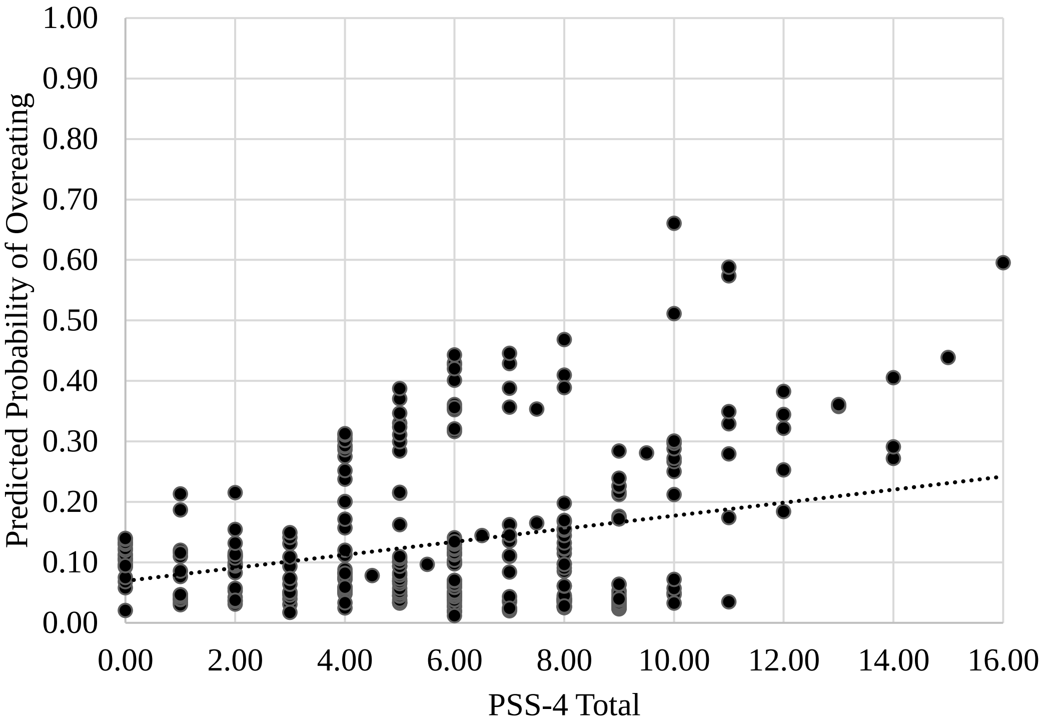


Figure 11. Predicted probability of overeating by self-reported stress from multilevel model during the seven day at-home period.

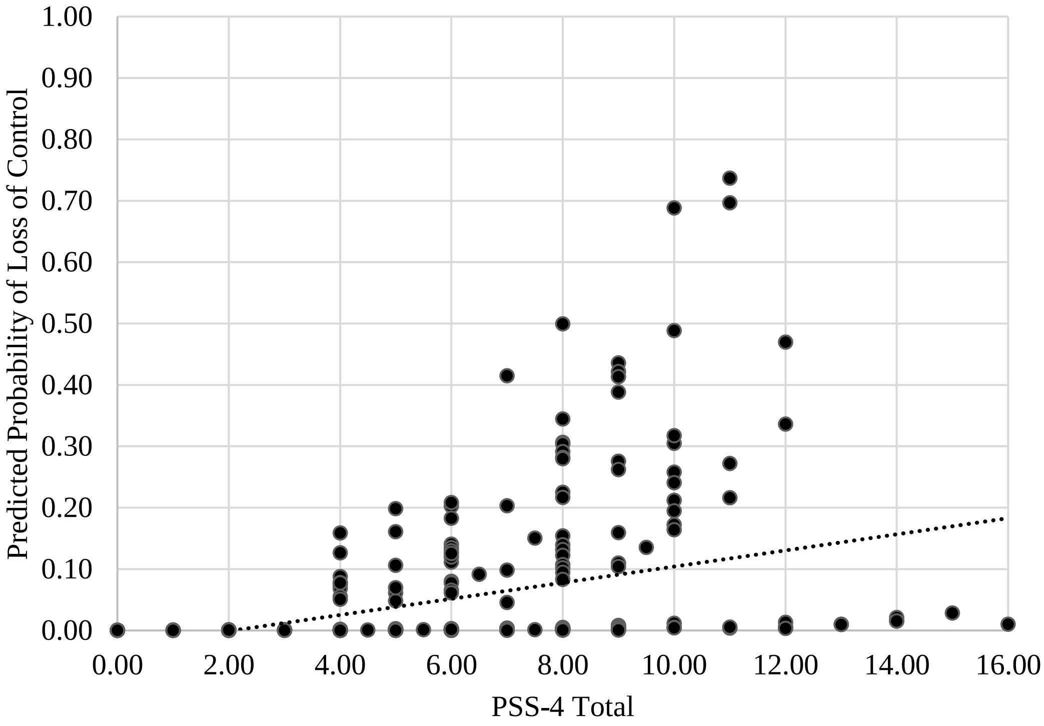


Figure 12. Predicted probability of loss of control over eating by self-reported stress from multilevel model during the seven day at-home period.

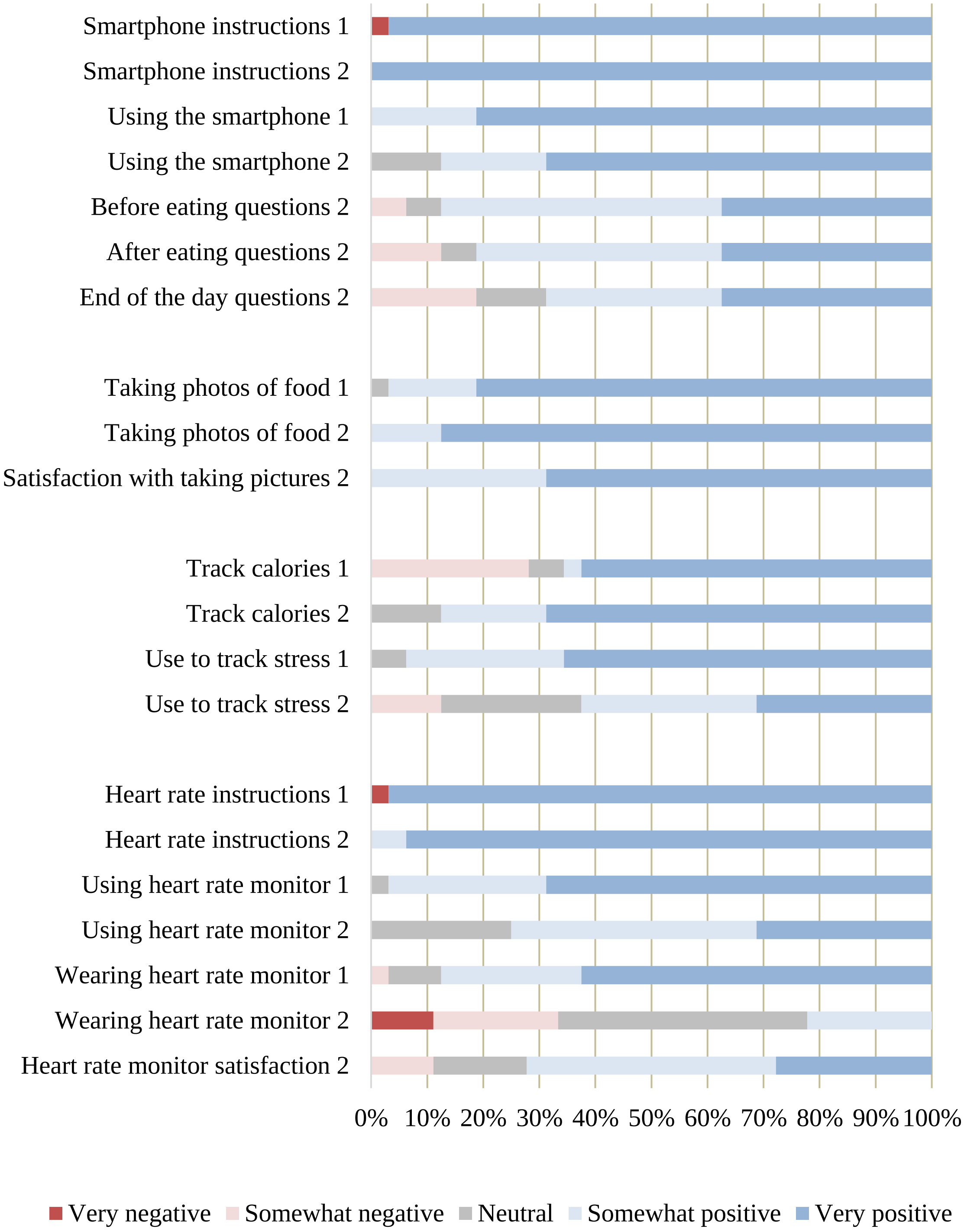


Figure 13. Results of self-reported satisfaction and usability questions from first (1) and second (2) lab visits.

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Appendix A: Questionnaire packet for post-training

SmHEARTphones:

Heart health and health behaviors study

Post-Training Smartphone Questionnaire Packet

General Instructions

Please do your best to respond fully to each question, even if it seems repetitive. We chose each question carefully and each question is of interest in examining stress, mood, and eating. If you are unsure of an answer, please make your best guess.

- Use **blue** or **black** ink only, do **not** use pencil

- Write your answer in the space provided.

Example:

What country were you born in?	United States of America

- Fill in the bubbles completely
  Example: ● ○ ○ ○

- Circle ratings
  Example:

Never	Rarely	Sometimes	Regularly
[✓ 0]	1	2	3
0	1	2	[✓ 3]

- Change your mind? If you need to change an answer, put an "**X**" through the answer you do **not** want
  Example:

☒ ○ ● ○

Example:

Never	Rarely	Sometimes	Regularly
[✓ 0]	1	2	~~[✓ 3]~~

Please answer the following questions by thinking about the system as a whole (smartphone to answer questions and take photos of food and the heart rate monitor):	Strongly disagree				Strongly agree
Q1. I think I would like to use this system frequently	1	2	3	4	5
Q2. I found this system unnecessarily complex	1	2	3	4	5
Q3. I thought the system was easy to use	1	2	3	4	5
Q4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
Q5. I found the various functions in this system were well integrated	1	2	3	4	5
Q6. I thought there was too much inconsistency in this system	1	2	3	4	5
Q7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
Q8. I found the system very cumbersome to use	1	2	3	4	5
Q9. I felt very confident using this system	1	2	3	4	5
Q10 I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

Instructions

Q11. How would you rate your satisfaction with the in-person instructions on how to use the smartphone application?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

Q12. How would you rate your satisfaction with the in-person instructions on how to use the heart rate monitor?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

Smartphone application for answering questions

Q13. Overall, using the smartphone to answer questions was:

1 Very difficult	2	3	4	5 Very easy

Photos of food

Q14. Taking photos of food was

1 Very difficult	2	3	4	5 Very easy

Q15. If you could track your food and eating (foods eaten, calories, etc.) using the photos taken with the smartphone app, how likely would you be to use it?

1 Very unlikely	2	3	4	5 Very likely

Heart rate monitor

Q16. Using the heart rate monitor was

1 Very difficult	2	3	4	5 Very easy

Q17. Wearing the heart rate monitor was

1 Very uncomfortable	2	3	4	5 Very comfortable

Q18. If you could track your stress levels using this heart rate monitor how likely would you be to use it?

1 Very unlikely	2	3	4	5 Very likely

Thank you for completing this questionnaire packet!

Appendix B: Smartphone attitudes and self-efficacy questionnaires given at first lab visit

Attitudes about Smartphones

These questions are designed to measure attitudes towards the use of smartphones in our society. It is not a test, so there are no right or wrong answers. Using the scale below, indicate your level of agreement or disagreement in the space which is next to each statement

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
B1. Smartphones will never replace human life.	1	2	3	4	5
B2. Smartphones make me uncomfortable because I don't understand them.	1	2	3	4	5
B3. People are becoming slaves to Smartphones.	1	2	3	4	5
B4. Smartphones are responsible for many of the good things we enjoy.	1	2	3	4	5
B5. Soon our lives will be controlled by smartphones.	1	2	3	4	5

B6. I feel intimidated by smartphones.	1	2	3	4	5
B7. There are unlimited possibilities of smartphone applications that haven't even been thought of yet.	1	2	3	4	5
B8. The overuse of smartphones may be harmful and damaging to humans.	1	2	3	4	5
B9. Smartphones are dehumanizing to society.	1	2	3	4	5
B10. Smartphones can sometimes eliminate a lot of tedious work for people.	1	2	3	4	5
B11. The use of smartphones is enhancing our standard of living.	1	2	3	4	5
B12. Smartphones turn people into just another number.	1	2	3	4	5
B13. Smartphones are lessening the importance of too many jobs now done by humans.	1	2	3	4	5
B14. Smartphones are a fast and efficient means of gaining information.	1	2	3	4	5
B15. Smartphones intimidate me because they seem so complex	1	2	3	4	5
B16. Smartphones will replace the need for working human beings.	1	2	3	4	5

B17. Smartphones are bringing us into a bright new era.	1	2	3	4	5
B18. Soon our world will be completely run by smartphones.	1	2	3	4	5
B19. Life will be easier and faster with smartphones.	1	2	3	4	5
B20. Smartphones are difficult to understand and frustrating to work with.	1	2	3	4	5

Attitudes about Smartphone Applications

Often we are told about smartphone applications (apps) that are available to make life easier. For the following questions, imagine that you were given a new smartphone app for some aspect of your life. It doesn’t matter specifically what this smartphone app does, only that it is intended to make your life easier and that you have never used it before.

The following questions ask you to indicate whether you could use this unfamiliar smartphone app under a variety of conditions. For each of the conditions, please indicate whether you think you would be able to complete the task using the smartphone app. Then, for each condition that you answered “yes,” please rate your confidence about your first judgment, by circling a number from 1 to 10, where 1 indicates “not at all confident,” 5 indicates “moderately confident,” and 10 indicates “totally confident.”

For example, consider the following sample item:

I COULD COMPLETE THE TASK USING THE SMARTPHONE APP…

EXAMPLE			NOT AT ALL CONFIDENT				MODERATELY CONFIDENT					TOTALLY CONFIDENT
	…if there were someone giving me step-by-step instructions	[✓ Yes]	1	2	3	4	[✓ 5]	6	7	8	9	10
		No										

The sample response shows that the individual felt he or she could complete the task using the smartphone app with step by step instructions (YES is circled), and was moderately confident that he or she could do so (5 is circled)

I COULD COMPLETE THE TASK USING THE SMARTPHONE APP…

			NOT AT ALL CONFIDENT				MODERATELY CONFIDENT					TOTALLY CONFIDENT
C1.	…if there was no one around to tell me what to do as I go.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C2.	…if I had never used an app like it before.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C3.	…if I only had a website for reference.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C4.	…if I had seen someone else using it before trying it myself.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C5.	…if I could call someone for help if I got stuck.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C6.	…if someone else had helped me get started.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C7.	…if I had a lot of time to complete the task for which the app was provided.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C8.	…if I had just the built-in help function for assistance.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C9.	…if someone showed me how to do it first.	Yes	1	2	3	4	5	6	7	8	9	10
		No										
C10.	…if I had used similar apps before this one to do the same task	Yes	1	2	3	4	5	6	7	8	9	10
		No										

Appendix C: Questionnaire packet for second lab visit

Date Packet Completed	

SmHEARTphones:

Heart health and health behaviors study

Second Lab Visit Questionnaire Packet

General Instructions

Please do your best to respond fully to each question, even if it seems repetitive. We chose each question carefully and each question is of interest in examining stress, mood, and eating. If you are unsure of an answer, please make your best guess.

- Use **blue** or **black** ink only, do **not** use pencil
- Write your answer in the space provided.

Example:

What country were you born in?	United States of America

- Fill in the bubbles completely
  Example: ● ○ ○ ○
- Circle ratings
  Example:

Never	Rarely	Sometimes	Regularly
[✓ 0]	1	2	3
0	1	2	[✓ 3]

- Change your mind? If you need to change an answer, put an “**X**” through the answer you do **not** want
  Example:

~~●~~ ○ ● ○

Example:

Never	Rarely	Sometimes	Regularly
[✓ 0]	1	2	~~[✓ 3]~~

R. Overall study

R1. How would you rate your overall satisfaction in participating in this study?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

R2. Participating in this study was

1 Very difficult	2	3	4	5 Very easy

R3. This study

1 Did not meet my expectations	2	3	4	5 Met my expectations

Please answer the following questions by thinking about the system as a whole (smartphone to answer questions and take photos of food and the heart rate monitor):	Strongly disagree				Strongly agree
R4.I think I would like to use this system frequently	1	2	3	4	5
R5. I found this system unnecessarily complex	1	2	3	4	5
R6. I thought the system was easy to use	1	2	3	4	5
R7. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
R8. I found the various functions in this system were well integrated	1	2	3	4	5
R9. I thought there was too much inconsistency in this system	1	2	3	4	5
R10. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
R11. I found the system very cumbersome to use	1	2	3	4	5
R12. I felt very confident using this system	1	2	3	4	5
R13. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

S. Instructions

S1. How would you rate your satisfaction with the in-person instructions on how to use the smartphone application?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

S2. How would you rate your satisfaction with the in-person instructions on how to use the heart rate monitor?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

T. Smartphone application for answering questions

T1. How would you rate your satisfaction with using the smartphone for answering questions before eating?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

T2. How would you rate your satisfaction with using the smartphone for answering questions after eating?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

T3. How would you rate your satisfaction with using the smartphone to answer questions at the end of the day?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

T4. Overall, using the smartphone to answer questions was:

1 Very difficult	2	3	4	5 Very easy

T5. During the at-home part of the study (7 days), how often did you remember to answer the questions before or after you ate? (check one box for each row in the table below)

	100% of the time	75% of the time	50% of the time	25% of the time	<25% of the time
a.Yesterday	5	4	3	2	1
b.2 days ago	5	4	3	2	1
c.3 days ago	5	4	3	2	1
d.4 days ago	5	4	3	2	1
e.5 days ago	5	4	3	2	1
f.6 days ago	5	4	3	2	1
g.7 days ago	5	4	3	2	1

T6. If you forgot to answer the questions at any point, please write the reason

U. Photos of Food

U1. How would you rate your satisfaction with using the smartphone for taking pictures of food?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

U2. Taking photos of food was

1 Very difficult	2	3	4	5 Very easy

U3. If you could track your food and eating (foods eaten, calories, etc.) using the photos taken with the smartphone app, how likely would you be to use it?

1 Very unlikely	2	3	4	5 Very likely

V. Heart Rate Monitor

V1. How would you rate your satisfaction with the 1 day of at-home use of the heart rate monitor?

1 Extremely unsatisfied	2 Somewhat unsatisfied	3 No opinion	4 Somewhat satisfied	5 Extremely satisfied

V2. Using the heart rate monitor was

1 Very difficult	2	3	4	5 Very easy

V3. Wearing the heart rate monitor was

1 Very uncomfortable	2	3	4	5 Very comfortable

V4. If you could track your stress levels using this heart rate monitor how likely would you be to use it?

1 Very unlikely	2	3	4	5 Very likely

W. Changes and Special Circumstances

W1. While you were participating in the study did you start any health promoting activities, for example, join WeightWatchers, or an exercise group?

1 No	2 Yes

W1a. If yes, please specify what activities

W2. While you were participating in the study did you follow your usual routine or did something unexpected happen that might have affected your stress, for example, did you have an accident/injury? (circle one)

1 No, I followed my usual routine	2 Yes, something unusual happened

W2a.If you selected YES, Please specify what happened, and when it happened:

W3. While you were participating in day 6 of the study (wearing the heart rate monitor) did you follow your usual routine or did something unexpected happen that might have affected your stress, for example, did you have an accident/injury? (circle one)

1 No, I followed my usual routine	2 Yes, something unusual happened

W3a.If you selected YES, Please specify what happened, and when it

W4. While you were participating in the study did you follow your usual routine or did something unexpected happen that might have affected your eating habits, for example, did you have any celebrations or travel? (circle one)

1 No, I followed my usual routine	2 Yes, something unusual happened

W4a. If you selected YES, Please specify what happened, and when it happened

Thank you for completing this questionnaire packet!

Appendix D: Semi-structured interview for second lab visit

- *“we are now ready to do a brief interview about your experiences in the study. For this part, I will record the interview to be transcribed at a later date. After the transcription, the recording will be deleted and won’t be associated with your file.”*
- Turn on the recorder and note the participant ID, “participant ID ______”
- Proceed according to the semi-structured interview:

1. What was your overall experience participating in this study? Any reactions or responses you would like to share?:
2. Comments on using the smartphone:
    a. How much did you remember to use it?
    b. What was it like to answer questions on your smartphone before eating?
    c. What was it like to answer questions on your smartphone after eating?
    d. What was it like to answer questions on your smartphone at the end of the day?
    e. What was it like to take photos of the food you were about to eat with your smartphone?
    f. What did you like most about using the smartphone for the study?
    g. What did you like least about using the smartphone for the study?

    h. Any issues that you encountered?
3. Comments on ease of use for the heart rate monitor:
    a. Did you remember to wear it?
    b. How easy/difficult was it to operate?
    c. Any issues that you encountered?
    d. How comfortable/uncomfortable was it to wear all day?
    e. How would you feel about wearing the heart rate monitor for the full 7 days of the study period?
    f. Would it be comfortable to wear the heart rate monitor for the full 7 days of the study period?
4. What parts of the study (lab visits, at home portion) did you like the most?
5. What parts of the study (lab visits, at home portion) did you like the least?
6. For whom do you think the study smartphone application might work particularly well?
7. Are there any groups of people for whom you think the study smartphone application might not work well?
8. What suggestions do you have for future research using these devices to study stress and eating?

Potential clinical utility

Imagine that after having done a 7 day at-home protocol, like the one you just completed, you could receive a personalized feedback form like the example below:

Your Stress and Eating Profile

Based on your stress and eating assessment, for you…

…the link between stress and eating is:

Weak / Very Weak / Strong / Very Strong

…the type of eating behavior to watch out for is:

Overeating / Empty Calories / Loss of Control / Breaking Dietary Rules

…the emotions that most trigger this eating behavior are:

Stress / Pain

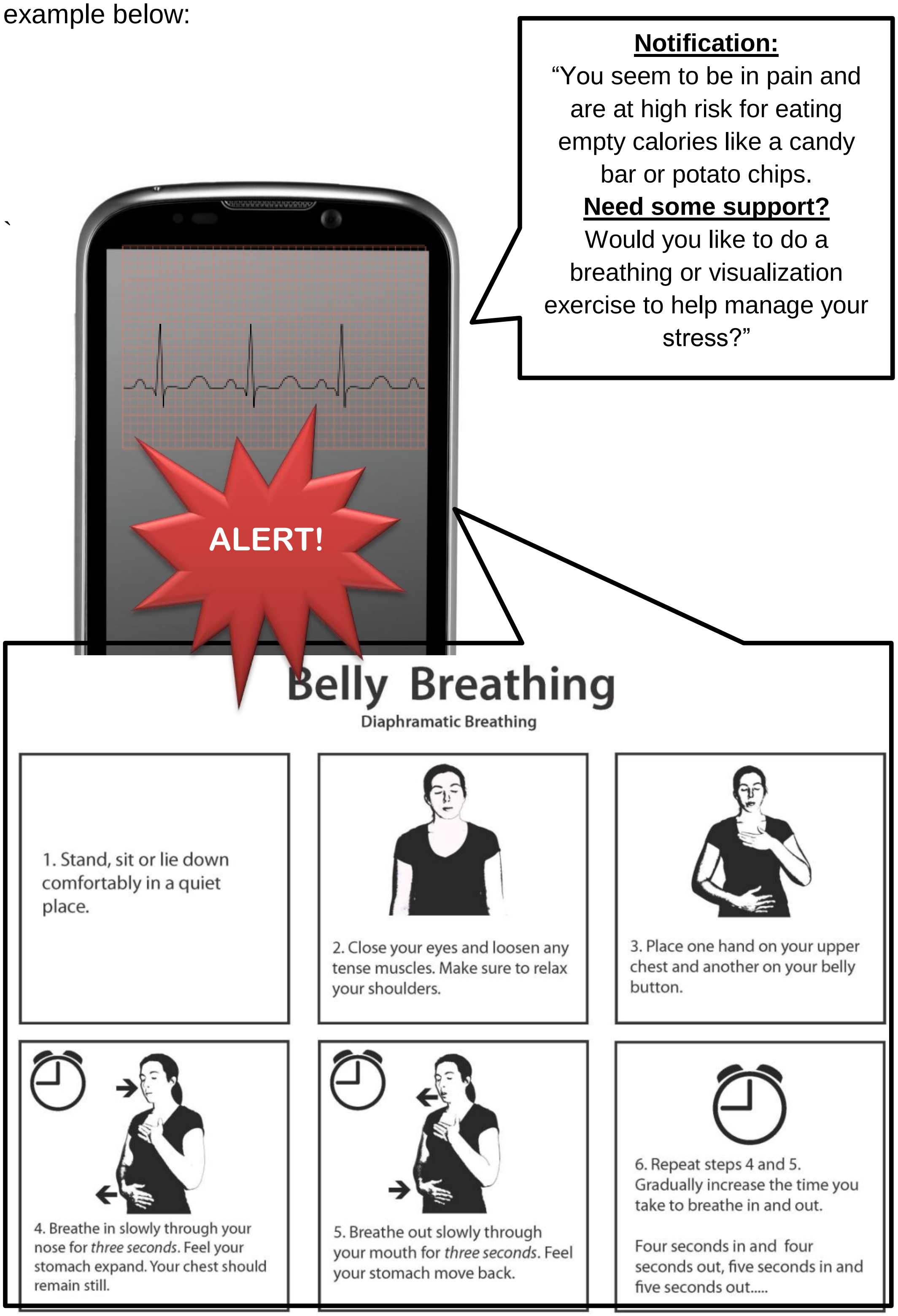
9. What would be your impressions of getting this kind of information?
10. How useful would it be to have this information?
11. What concerns would you have about this information?
12. Would you share this information with anybody (partner, friend, healthcare provider)?

Imagine that while you are using the study smartphone you could receive a personalized feedback warning you that you may do some unhealthy eating like in the example below:

Notification:
"You seem to be in pain and are at high risk for eating empty calories like a candy bar or potato chips.

13. What would be your impressions of getting this kind of information?
14. How useful would it be to have this system?
15. What concerns would you have about this system?
16. How interested would you be in using this system for a short period of time (e.g., 1 week)?
17. How interested would you be in using this system for a longer period of time (e.g., 1 year)?

Now imagine that while you are using the study smartphone you could receive a personalized feedback AND a way to help you cope like in the example below:



Notification:
"You seem to be in pain and are at high risk for eating empty calories like a candy bar or potato chips.
Need some support?
Would you like to do a breathing or visualization exercise to help manage your stress?"

Belly Breathing
Diaphramatic Breathing

1. Stand, sit or lie down comfortably in a quiet place.

2. Close your eyes and loosen any tense muscles. Make sure to relax your shoulders.

3. Place one hand on your upper chest and another on your belly button.

4. Breathe in slowly through your nose for *three seconds*. Feel your stomach expand. Your chest should remain still.

5. Breathe out slowly through your mouth for *three seconds*. Feel your stomach move back.

6. Repeat steps 4 and 5. Gradually increase the time you take to breathe in and out.

Four seconds in and four seconds out, five seconds in and five seconds out.....

18. What would be your impressions of getting this kind of information?
19. How useful would it be to have this system?
20. What concerns would you have about this system?

21. How interested would you be in using this system for a short period of time (e.g., 1 week)?

22. How interested would you be in using this system for a longer period of time (e.g., 1 year)?

Appendix E: Code book for semi-structured interview qualitative content analysis.

Research question: what were participants' experiences participating in the study (eating behavior, smartphone, HR monitor), including suggestions for future research?

		Code	Code definition	Examples from the data
Behavior		**Changed eating**	Avoided, delayed, or slowed eating during the study. Eating behavior changed due to using study app.	"I don't think I had seconds at all this week, and part of that is I saw the picture of the first plate. I would snap the picture and put the phone away, but I knew what the photo looked like and I didn't want to take another picture. So that was the deterrent. I don't want to take a picture of another plate."
		Attention	Increased attention while eating. No longer eating mindlessly, eating more purposefully, more aware of their eating, or more aware of how emotions relate to eating.	"Now I will eat which means now I will record. It makes you more engaged, more conscious. Food time is coming so I will record. It makes you more cognitive and more engaged in the process of eating, what you are going to eat and all that even though you didn't record it. It was just simply being aware."
		Reviewed food intake	Reviewed what they had just eaten or how their eating had been that day. Reviewed their patterns of eating over a few days while in the study.	"It was a good reflection that gave me an opportunity to kind of evaluate"
		Technical error	Technical errors (e.g., random buzzing reminding them to finish a survey or hit the wrong button to start a survey).	"It rang when it wasn't supposed to ring."

Behavior		**Forgot to log**	Forgot to log or record their eating as instructed, even if remembered later.	"There were sometimes where I would catch myself in the middle of eating and then I'd go and fill it out"
		Forgot how to operate it correctly	Forgot proper or instructed operation of the smartphone, app, or HR monitor.	"It was a little tricky to turn off. I remember there were two buttons to push and I didn't bring the instructions with me. So I had to call my husband to have him send me a screenshot of the instructions on how to turn it off."
		Clothing/ activities	Chose clothing or activities that were compatible with the HR monitor.	"I just tried to tuck my t-shirt under the fabric to get a little relief. I was just like I'm not going to work out today. I was like it's the afternoon and I'm already raw so the dog walk will be it for today."
3	**Emotions related to eating behavior**	**Frustrat-ion**	Frustrated about having to log for the study.	"It's just like if you are going to break a habit maybe it's going to be a little frustrating at first. Like if I wanted to get a little snack in between [meals], I'd have to go like is this worth doing this survey and marking it down, and then I was like do I really want to mark down that I had 6 meals today"
		Urges/ hunger	Noticed urges to eat and sensations of hunger/fullness.	"It was a nice review to think about, what did I eat, how much did I eat, how do I feel, am I uncomfortably full, regularly full?"
	Emotions related to study tasks	**Positive emotions**	Expressed positive feedback or reported a good experience with a study task.	"That was good, that was a good question" "Overall very pleasant experience."
		Neutral emotions	Expressed a neutral emotion to study task.	"I'm pretty neutral about the rest of it" "Overall experience was fine"

Emotions	**Emotions related to study tasks**	**Negative emotion**	Expressed annoyance or another negative reaction to a study task.	“The questions were kind of uncomfortable” “It’s embarrassing, like oh that’s a lot of food. I ate a lot of food” “I didn't like it.”
		Unsure how to log	Unsure how to log or record for the study.	“I was confused. There was no marker that this was done and that this should be done after that.”
		Acclimated	Got used to the HR monitor it or found it mostly comfortable.	“Sometimes you didn’t know it was there. Comfortable and not comfortable. Tolerable. It got easier towards the end of the day. I had worn it during the rest of the day so I got used to it.”
		Irritated/ bulky	HR monitor caused irritation, discomfort, or itching. Reported it to be bulky.	“I think it was the electrode pad, was like starting to irritate my skin.”
		Unsure/ hesitant about long term wear	Noticed the HR monitor later in the day or were unsure about using it for a long period of time.	“I don't know if I would like to wear it every day, but you know for that day it was ok.”
Thoughts / Perceptions	**Usability**	**Simple/ easy**	Study tasks easy, simple, or straightforward.	“There was only one question so that was pretty easy.” “The questions were simple. It was all pretty straightforward.”
		Repetitious	Questions were repetitious.	“Having the same questions seemed to be redundant.”
		Convenience/ speed	Logging on a phone was convenient or fast.	“For me it's something I carry around all the time. It was just a matter of grabbing it and eating my food so I thought it was pretty convenient. “
		Suggestions for improvement	Suggested improvements for the study.	“If this were an app on my own smartphone, I’d want a calendar feature with a reminder feature. or even just a check mark one I’ve completed it for each meal"

Thoughts / Perceptions	**Fits into life**	**Photos +**	Taking photos of food was relatively easy, common, or useful.	“I liked the taking the photos of the food the most just because I'm used it and it was easy.”
		Photos -	Raking photos of food was negative.	“It can be a little awkward if you are somewhere else and you are taking pictures. But at home it feels comfortable.”
		Logging -	Logging was perceived as negative or not socially normative.	“There were a couple times when I'd go out to eat with some friends and appetizers come out before a main dish and everybody starts munching on appetizers before the main dish then it’s like lemme fill this out real quick on the side and keep going.”
		Age	Older people might struggle with the study app.	“Like my parents I don't anticipate them really carrying or taking pictures of their food. I don't anticipate this being a natural transition for them.”
		Familiar-ity with tech	Familiarity with and convenience of technology influences app use.	“I know how to use smartphones to it was easy. It's a technology I'm familiar with.”
		Interest in health	Interest in health or changing eating habits might make people more interested in using the study app.	“I think people who are, like I'm in weight watchers for example. I know lots of people in weight watchers who struggle with overeating and emotional and stress eating.”
		Daily pace/ demands	Some people may have responsibilities and commitments that interfere with using the study app.	“I would always forget because I’m always in a hurry when I eat”
		Could make time for it	Able to make time for completing study tasks, or tasks are easy once they form the habit.	“I can do that all the time.”

Research question: what are participants' reaction on proposed ways to use these devices for clinically?

	Code	Code definition	Examples from the data
Personalized	**More triggers/ behaviors**	Want to track more triggers and behaviors.	"I know there are ways to have the system respond to what I enter. so if I know that I walk into my office and pass a candy jar and Monday and Tuesday I pass it and on Wednesday I trigger the system, and it asked me a question, but if it learns who I am based on previous responses, it would be more complex."
	Details about eating behavior	Want detailed feedback on eating behavior and the important variables across episodes or time to increase awareness and change their eating.	"if I could put it on my phone or if it just had the ability for me to a get a summary out of it that I could share, even if there was the ability to get a report on a weekly or monthly basis that showed the time of day and days of the week, like if I could see the pattern. I could see like every Tuesday at 4 pm I'm eating poorly, why is that? Oh right that's when I see my ex-husband. It kind of helps you see the obvious."
	Range of coping strategies	Want a customizable range of strategies to help reduce stress or encourage behavior change.	"If you are saying I can only have breathing. Sometimes the scenario isn't applicable for breathing, but other times maybe I just need to see a kitty video today."
Alerts	**Increase stress**	Alerts might increase stress or make people more annoyed in the moment.	"I think it would add more stress for me personally. It really would, especially if there wasn't an action part. If it was just like "alert!" it's just like somebody running around saying danger all the time. It would be a little stressful."
	Presume behavior	Don't want their behavior assumed or predicted. A check in is preferable to assuming unhealthy eating. Don't like having smartphones telling them what to do.	"I might be annoyed at first. It's like, I'd feel like I'd be annoyed at first. Why are you telling me what to do? Why are you making this assumption of me? I'd be annoyed, especially if it were worded in this way so I probably wouldn't go for it. I'd probably get sick of it really fast."

Alerts	**Accuracy /frequency**	Alerts need to be accurate and infrequent or else they will be annoying or ignored.	“If it came up 3-4 times in a day, that's a problem. If it came up more often than it should that's a problem.”
	Ignore	Not the type of person who attends to smartphone alerts or notifications and will likely ignore them	“In the beginning it would be fine. But after a while if it started getting on my nerves, I'd be like this thing is getting on my nerves. How do I shut it off?”
	Customize	Alerts have to be customizable in content and presentation and should be able to be snoozed	“So if I have control to say today I’ll listen to the warnings but tomorrow leave me alone. I would like the choice of setting the alerts on or off.”
	Helpful	Alerts or static feedback about the emotion-eating behavior relationship would be helpful in making behavior change.	“This kind of alert might help me. Instead of eating potato chips why don't you go out and play something.” “I think it would help halt some of those ingrained behaviors.”
Information Sharing	**Privacy**	Concerned about sharing information about eating due to privacy concerns.	“As long as it doesn’t go to a doctor or something…that would get me to come see him or a service. You wouldn’t give it to somebody and they would contact me to buy nutritious foods or something like that.”
	Help intervene	Would share with people who could directly help intervene or support change.	“I'd share it with my partner who I live with and eat with a lot. I'd share it with another woman who I'm close to who works on food issues and weight. I'd share it with my nutritionist and any other medical professional who is working with me on stress.”

Interest and engagement	**Habit**	Long term use of the study system has to be a habit or result from benefit of using the app.	“Well the problem with a year is that you might not remember to do it on a daily basis. Unless you remember to do it on a daily basis it's not going to be beneficial”
	Not interested	Not interested in longer term use of the study system or has a negative view of long term use.	“On my own for free I'd probably get bored of it after a few weeks.” “Only as it's set up right now? No. it wouldn't be something I would use.”
	Open/ curious	Open to using the system and curious about what they might find out or discover. Would try it.	“Possibly. I mean if it helped me achieve my goals that would probably be a good thing.” “I would be trying to figure out “where'd they get this information?”. How they got it.”
	Open/ positive expectations	Open to using the system again and would expect to have a positive experience or that the system would promote positive change.	“I think that might change my life because it would create a habit, when you get stressed, create something else…longer term I think it would change your whole mindset about dealing with stress.”
	Compatibility with technology	Long term use will be improved if the study system is compatible with familiar/used technology.	“Pairing it with the Fitbit. That kind of thing seems like it would be super awesome. everybody has a Fitbit now”
	Stigma	Concerns about stigma.	“Other people seeing it on my phone. Like if my phone were on my desk and they saw it and thought it was weird. People who don't tend to like that much information about themselves might think that it's weird that I like that or that I need to remind myself of those things. It can come off as like a sign of weakness. I don't think it's a sign of weakness. I think it's acknowledging that we are in a very stressful environment and we need to have these reminders in our lives. but that social pressure of having someone else see it”