Chapter 7

Measuring Satiation and Satiety

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1 INTRODUCTION

The initiation and termination of an eating episode is a complex behavior that involves many regulated parameters. Consumer food intake and post-ingestive experience are quantifiable and provide important insights into the habitual dietary patterns and intake behaviors that inform health and well-being. However, at the heart of these measures are human subjects, with all the subjectivity, idiosyncrasy, and complexity often associated with human sensory and consumer testing. In recent years there has been a rise in functional satiety claims for foods, with terms like “fuller for longer” used to describe a satiating product experience. For these claims to be credible, experimental findings must be reliable and reproducible if they are to support product development or claim substantiation. To ensure these data are robust and reliable, guidelines have been developed for accurate, reproducible, and discriminative approaches to measuring different aspects of the satiating properties of foods. There is an increasing awareness among sensory and consumer science researchers of the need to go beyond one-sip hedonic appraisals, to understand the experience of consuming a full product or meal and the subsequent post-ingestive experience (Lésédéma et al., 2016). This includes understanding eating behaviors that emerge during a meal, differences in the filling properties of different foods, the duration and quality of the fullness perceived, and the impact consumption has on later energy intake. This information enables a deeper understanding of the psychobiology of eating and the complex relationship between appetite, food choice, and energy intake regulation. In the past a significant focus in the satiety field has been on the satiety experience of consuming foods that differ in macronutrients or energy (Rolls, Hetherington, & Burley, 1988).

A wide range of factors influence the onset, timing, and duration of satiety feelings and these have been summarized in the “satiety cascade,” which illustrates the different timings of onset between satiation and satiety and the relative contributions of sensory and physiological influences (Fig. 7.1) (Blundell, 1991). Food sensory properties have an important role early in the satiation process, directing food choice behavior and informing portion selection pre-meal, and in the oral metering of calorie intake within a meal (McCrickerd & Forde, 2016). Physiological and endocrine processes have a strong influence later in the meal (Fig. 7.1). Accurately quantifying the factors that influence food intake within a meal, and from meal to meal, is central to an understanding of eating behaviors and the etiology of obesity, and can be used as the basis for approaches to improve weight management. As with sensory tests, the
approaches used to measure food intake and quantify the human subjective experience serve to control, partition, and reduce unwanted bias among the measures to yield an objective impression of the filling properties of foods. This chapter summarizes the most commonly used methods for quantifying satiation, satiety, and eating microstructure and will introduce the recently developed approach to measuring “expected satiety” for different foods.

2 A DEFINITION OF SATIATION AND SATIETY

Before discussing how best to measure satiation and satiety it is first necessary to define them, as these terms are often confused and used interchangeably, though both describe sensations that are physiologically and behaviorally distinct. Satiation describes the series of processes that bring a meal to an end, and is frequently associated with meal size (g or kcal). Satiety is used to describe the post-ingestive processes that occur after a meal and inhibit further eating, and includes the suppression of hunger and a feeling of fullness during the intermeal period, and is usually associated with measures of time until the next meal and/or later meal or snack intake (kcal) (Blundell et al., 2010). These processes are separate but overlapping, and both should be considered when evaluating the satiating properties of a food (Livingstone et al. 2000).

A study to understand the satiating properties of a food is focused on the intrameal period and measures energy intake, weight, or volume and changes in the subjective appetite feelings that occur before, during, and at the end of the meal itself. Satiation controls the size of a meal, whereas satiety is responsible for the duration of the intermeal interval, the frequency of eating, and the subjective appetitive feelings during the intermeal period. Satiety between meals can be quantified by tracking subjective feelings of hunger and fullness, time to the next meal, and energy intake at the next meal. Satiety can also be reflected in physiological measures such as gastric emptying or circulating levels of appetite peptides (Delzenne et al., 2010; Mars, Staffelau, & de Graaf, 2012). Differences between satiation and satiety are important to understand.
conceptually, as they help explain the theoretical independence of the techniques used in their measurement. Each sensation has distinct endocrine and physiological pathways that underpin the duration and intensity of their expression and are manifest as differences in behavior (Fig. 7.1).

Both the intensity and the duration of satiation and satiety can vary depending on the caloric, macronutrient, and sensory properties of the foods tested and an individual's response. As satiation describes the factors that lead to the end of the meal, key influences include food form (liquid, solid), energy density (kcal/g), and macronutrient composition (percentage of energy from fat, carbohydrate, protein), as well as the predominant sensory properties and intensities, including the palatability and variety of foods served. Satiety tends to be more influenced by food composition and total calories consumed, though clearly there is a strong interrelationship with satiation, as the amount consumed within a meal (satiation) strongly influences the feeling of fullness, duration of fullness between meals, and amount of energy consumed at a later meal.

Studying eating behaviors under the controlled conditions of the laboratory affords the opportunity to study psychobiological influences of energy selection and intake and, through well-designed and controlled studies, establish an understanding of factors that influence human appetite control. In an ideal world it would be possible to profile eating behaviors and energy intake across all meals and over time, controlling for the sensory and macronutrient composition of all foods consumed. However, in reality this is impractical. In the same way hedonic ratings on a 9-point scale are an approximation of liking, it is important to recognize that satiety techniques are at best an estimate of what occurs naturally in the real food environment, where product information is available, portions are often predetermined, and a wide range of social and psychological factors influence food choice and intake. Despite these limitations, the techniques presented hereafter describe the different approaches used to measure satiation and satiety.

3 MEASURING SATIATION AND SATIETY

Fig. 7.2 provides a schematic overview of several different approaches used for the measurement of satiation (Fig. 7.2(a)) and satiety (Fig. 7.2(b)–(d)) and an example of the application of each approach and key outcomes for comparison. An overview of the approaches used to measure satiation and satiety is provided next.

3.1 Measuring Satiation

An ad libitum meal paradigm is typically used to measure satiation, and in it the total energy or weight of food consumed to fullness is recorded and related back to either the properties of the test food or meal or differences within the
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FIGURE 7.2  Examples of different test protocols for the measurement and comparison of (a) satiation and (b–d) satiety.

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GROUP OF SUBJECTS CONSUMING IT (Chapelot, 2013). Within this same ad libitum meal paradigm it is also possible to capture food choice (Allirot et al., 2012), the microstructural patterns of eating during the meal (Bellisle & Le Magnen, 1980; Bolhuis et al., 2014), temporal changes in appetite feelings (Yeomans, 2000), and the reasons for cessation of eating (Mook & Votaw, 1992). This will be described in more detail later, when we focus on selecting test foods and additional measures. Regardless of the test food and meal paradigm chosen, numerous studies have shown that crossover (or paired/repeated measure) designs should be applied as a rule whenever possible instead of between-groups designs, as interindividual differences in food intake responses are large and may lead to unreliable data (Arvaniti, Richard, & Tremblay, 2000; Blundell et al., 2010; Chapelot, 2013; Gregersen et al., 2008). For example, crossover designs are appropriate when comparing the effect of an ingredient on fullness within the same group of subjects, whereas between-groups may be more appropriate when the outcome of the study can be significantly influenced by memory or learning and where balancing the order of presentation will not suffice in removing this effect. An example would be a study that seeks to explore the impact of high and low satiety labeling on subsequent food intake for the same food, where a washout period would be insufficient to remove the influence of the first session. Although less commonly used, between-groups designs are useful under specific circumstances provided each

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<table>
<thead>
<tr>
<th>Test stimulus / variable that is being measured for satiation or satiety</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) <strong>Satiation</strong> (ad libitum meal)</td>
</tr>
<tr>
<td>Overnight fasted</td>
</tr>
<tr>
<td>Fast breakfast</td>
</tr>
<tr>
<td>Pre-meal appetite ratings</td>
</tr>
<tr>
<td>Add libitum meal</td>
</tr>
<tr>
<td>90-120 min</td>
</tr>
<tr>
<td>Food diary for the rest of the day</td>
</tr>
<tr>
<td>Appetite ratings</td>
</tr>
<tr>
<td>Where to use this? Can be used to test the amount of energy that would be consumed if fullness, to compare the satiating (digestive) properties of different foods, or compare energy intake between different subject populations.</td>
</tr>
</tbody>
</table>

| (b) **Satiation** (fixed portion) |
| Overnight fasted |
| Fast breakfast |
| Pre-meal appetite ratings |
| Fixed portion meal |
| 90-120 min |
| Food diary for the rest of the day |
| Appetite ratings |
| Where to use this? Can be used to measure subjective feelings of fullness/hunger following a fixed portion of a food/drink that differentiate within individuals and differ in energy content, environment, or composition. |

| (c) **Satiation** (pre-load test meal design) |
| Overnight fasted |
| Fast breakfast |
| Pre-meal appetite ratings |
| Pre-load |
| 45-60 min |
| Add libitum meal |
| 50-120 min |
| Food diary for the rest of the day |
| Appetite ratings |
| Where to use this? Can be used to test the satiating properties of a test meal and the impact this has on feelings of fullness and later food intake (see McNicholas et al., 2010 for an example). |

| (d) **Satiation** (pre-load test meal with second meal) |
| Overnight fasted |
| Fast breakfast |
| Pre-meal appetite ratings |
| Pre-load |
| 90-120 min |
| Add libitum meal |
| + Food diary for the rest of the day |
| Appetite ratings |
| Where to use this? As with (b), this approach is used to measure subjective feelings of fullness following a fixed portion of a test meal, but here it is also possible to quantify intake at a later time, to test normal meal patterns (see Tray et al., 2010 for an example). |

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Key outcomes: Differences in post-meal appetite sensations and energy intake from an ad libitum meal.
group is adequately powered to reduce interindividual variation in appetite responses.

3.2 Measuring Satiety

Satiety captures the intensity and duration of the feelings of fullness derived from an eating event, and includes the subjective feeling of fullness between meals and the timing and extent of later calorie intake as key outcomes. A key distinction between the measurement of satiation and the measurement of satiety is that the latter considers temporal changes in subjective feelings of hunger and fullness for the energy consumed and impact of these feelings on the timing and extent of later energy intake (Chapelot, 2013). Satiety measures reflect changes in subjective motivation to eat between two time points and can be measured using fixed portions, preloads, or ad libitum test meals. Satiety can therefore be measured by (1) tracking changes in subjective need states over time (i.e., hunger/fullness/desire to eat) or by (2) measuring the duration between the treatment and the next meal and the intake at the next meal following the experimental treatment. Based on this, there are multiple outcomes used to measure satiety feelings. These are summarized in the following as either measures based on subjective feelings or objective measures of intermeal duration and later food intake.

3.3 Measuring the Intensity of Subjective Appetite Feelings

3.3.1 The Scaling of Appetite Need States

The scaling of appetite need states is usually captured on 100- or 150-mm visual analogue scales (VAS) and follows many of the same principals as described elsewhere for sensory attribute ratings (Lawless & Heymann, 2010). The reproducibility and reliability of a VAS line scale of appetite feelings have been extensively reviewed elsewhere (Flint, Raben, Blundell, & Astrup, 2000; Stubbs et al., 2000) and show good repeat reliability at the group level, but variable repeat reliability at the individual level. Most research recruits a minimum of 20–25 subjects to capture a 10% difference in average subjective appetite ratings between foods, with larger samples required for between-subjects comparisons and studies with multiple experimental conditions (Flint et al., 2000). These measures tend to be more robust in response to defined experimental manipulations compared to studies attempting to associate appetite feelings with satiety biomarkers (Blundell et al., 2010). The VAS line scale approach is widely applied because it is cheap, easy to understand and analyze, and predictive of later energy intake. In a review of 23 randomized eating studies, Sadoul and colleagues highlighted that a difference in appetite motivation VAS ratings of ≥15–25 mm on a 100-mm line scale was sufficient to predict a significant change in later energy intake (Sadoul, Schuring, Mela, & Peters, 2014). In a metaanalysis of 462 studies it was concluded that self-re-
ported appetite ratings do not reliably predict energy intake and emphasized the need for caution when inferring later intake from appetite ratings alone (Holt et al., 2016).

Category scales can also be applied instead of VASs and the two have been shown to have similar discriminative power (Jeon, O’mahony, & Kim, 2004), and subjects can make ratings on paper or using a computer-based electronic appetite rating scale (Almiron-Roig et al., 2009). Before the scales are presented to participants, attributes must be clearly defined using terms that are unambiguous and clearly understood by all participants, should be appropriately anchored, and should be unidimensional and not try to capture two sensations on the same scale. For example, ratings for hunger and fullness are not appropriate scale anchors on the same scale as it cannot be assumed there is an inverse or linear relationship between these feelings. When measuring satiety intensity posttreatment, a range of appetite need state measures should be taken at fixed time points after the meal or preload treatment. The choice of appetite attributes to be scaled posttreatment should be led by the hypothesis being tested and it is not advisable to measure multiple attributes and then post hoc select only the scales that produce the best result. An advantage of the VAS line scale approach is that it is reproducible and requires minimal data handling. Typically this involves measures of hunger, fullness, thirst, and desire to eat at baseline, before the treatment, and thereafter every 15 or 30 min for 90–120 min. Fullness is defined as the absence of hunger, whereas hunger is defined as a measure of the motivation to eat (Rogers & Hardman, 2015). Prospective consumption is often captured and is defined by asking how much a subject feels he or she could eat at that given moment. It is also possible to capture changes in food liking and palatability both during and after the treatment or test meal, and there is an important distinction to be made between the two. Palatability of a food will decrease the more of it you eat, as it is influenced by hunger and fullness; whereas food liking should remain stable and not be as influenced by need state (Rogers & Hardman, 2015).

Fig. 7.3 summarizes examples of some of the approaches used when scaling appetite sensations. Beyond the traditional VAS line scale (Fig. 7.3(a)) and category scale ratings (Fig. 7.3(b)) of appetite feelings, others have further developed composite measures of need state, such as the SLIM scale (satiety labeled intensity magnitude scale), in which several attributes can be combined (Fig. 7.3(c)). To avoid ceiling effects when scaling with appetite sensations, the labeled magnitude scale has been developed to cover appetite sensations (Solah et al., 2015). The SLIM is a vertical, 100-mm, bidirectional hunger–fullness scale that incorporates phrases describing different levels of hunger/fullness along the length of the scale, with “greatest imaginable fullness” and “greatest imaginable hunger” serving as anchors. SLIM has been shown to have sensitivity similar to that of the VAS for measuring perceived appetite (Cardello, Schutz, Leshner, & Merrill, 2005; Karl, Young, Rood, & Montain, 2013). More recently, new approaches have emerged using meal pictures to
contextualize the ratings of prospective consumption, and these have demonstrated improved discrimination over traditional VAS hunger and fullness scaling (Sadoul et al., 2012). Finally, there are also a range of nonverbal/unlabeled techniques using pictures that can be used when scaling hunger and fullness sensations (Fig. 7.3(d)). These intuitive scales provide category-level information and can be used with subjects that have poor literacy or to avoid the need for translation of scale instructions or anchors. When studying fullness and hunger among children, we cannot assume they will understand the scaling approach or the visceral feeling of hunger and fullness sensations. A new scale has been developed for research on satiety feelings with children (Bennett & Blissett, 2014). The scale is supported by a story to engage children to recognize feelings of hunger and fullness through a character named “Teddy the Bear” and has been validated for use with children to facilitate accurate and reliable ratings of hunger/satiety in children for whom abstract sensations like hunger and fullness can be difficult to interpret and quantify (Fig. 7.3(e)).
3.3.2 Time Course and Indices of Satiety Sensations

As we often have no a priori knowledge of the timing of onset or decay of the fullness imparted by a test stimulus, often before formally running the satiety trial it is advisable to run a time course analysis to understand the changes in appetite sensation over time for a specific stimulus. This enables the experimenter to design a test protocol that maximizes the sensitivity of the comparisons between the test stimuli being compared. For example, if the test includes both sensory and energy density manipulations within a set of products, the sensory effect would be expected to occur early in the time course, but the macronutrient or energy density effects will probably have their own time course and will be dependent on gastric emptying rate and assimilation of energy postingestively. If the time course of appetite measures postingestion is too short, it is possible to miss the key periods of satiety that discriminate between the food treatments being compared. Once the optimum time course for the measures has been defined, the intensity of the different appetite ratings is captured at each time point pre- and posttreatment, usually at 15- or 30-min intervals. These ratings can be plotted to compare the slope, maximum rise, and decay of the feelings hunger/fullness for each test treatment. These ratings capture the subjective impression of the satiety imparted by a test treatment, and so can be averaged across individuals at each time point to enable a robust comparison of the subjective experience of each condition. Fig. 7.4(a)–(c) shows examples of such curves for (Fig. 7.4(a)) rated hunger and fullness over time, (Fig. 7.4(b)) the key peaks and troughs used for comparison of fullness over time, and (Fig. 7.4(c)) a hypothetical example of a curve for a fullness comparison between two food stimuli. From these plots, it is possible to compare the intensity and experience of satiety for each treatment by the rate of onset and decay of changes in the ratings (slope), the timing and intensity of the maximum feeling of fullness imparted (“peak fullness”), and the total duration of satiety experienced (area under the curve). Owing to the large individual variations in appetite ratings, averaged scores should be taken at each time point for the area under the curve (AUC) calculation, as this is much better than individual absolute ratings at single time points (Flint et al., 2000). The AUC is typically calculated using a trapezoid approach and can be compared for incremental AUC, which provides a summary of the onset and decay of the feeling of fullness, or total AUC, which provides a total for the fullness perceived across test treatments (Fig. 7.4(b)). The “satiating power” of the treatment can then be derived by diving the total AUC for the fullness imparted by the energy (kcal) consumed for the test treatment (Blundell, Rogers, & Hill, 1987). A related measure called the “satiety index” can be calculated by looking at the ratio of the AUC for a test food or treatment to the AUC for a standard food (Holt, Brand, & Petocz, 1996; Weight, 1995). Similarly, it is possible to compare the functional benefit of food intake by deriving a “satiety
Part II Health-Related Issues

(a) 100

(b) 100

(c) 100

Tests meal 1

Tests meal 2

Duration

Peak fullness

Total AUC
FIGURE 7.4  (a) Fullness and hunger curves, (b) satiety calculations, (c) fullness comparison between two samples. AUC, area under the curve.

quotient,” for which the difference in the hunger before and after food intake is calculated as a function of the energy content of the food consumed (Green, Delargy, Joanes, & Blundell, 1997). Finally, the “satiety ratio” can be derived as the ratio between meal size (kcal) and the latency to the onset of the next meal (time) (De Castro and Brewer, 1992). Collectively these indices offer a standardized approach for comparing subjective satiety experience per kilocalorie consumed, across treatments and test populations.

In 2016, a trained sensory panel approach was adopted to develop a high-throughput satiety panel approach for the objective comparison of the satiating properties of different foods. To achieve this, a group of sensory panelists underwent training to improve their use of an appetite vocabulary to scale sensations of hunger and fullness and reproducibly rate these sensations. Results from this approach were shown to be reproducible, and the approach showed stronger discrimination of perceived satiety for a set of cereal products than the same ratings made by a group of naïve consumers (Lesdëma et al., 2016). This new approach highlights a growing interest in the measurement of the subjective experience of satiety and creates an opportunity to rapidly screen products by differences in the satiety they can deliver. However, the satiety panel approach may lack ecological validity as it reflects real-life ingestive behavior poorly. For this reason it would be useful to use a satiety panel to screen differences in products, but to test the satiating efficacy of the foods in a more natural free living eating context.

3.3.3 Equilibrating Participant Need State at the Beginning of a Food Intake Trial

At the beginning of a food intake trial it is desirable that subjects arrive in equivalent need states, so that the visceral feelings of hunger, fullness, and desire to eat that will be measured over the course of a test session are similar at baseline before the test treatment or meal is consumed. It is not possible to fully control this owing to naturally occurring differences in eating patterns and differential energy requirements across the test population. One approach that is used to counter the variance from differences in starting need state is the use of the correct randomization procedure to ensure that the variance from small differences in need state is spread evenly over the different test days and treatments. In addition, it is common practice to advise against strenuous exercise the day before a trial, to discourage subjects from arriving with significant energy depletion that may prompt additional calorie intake, independent of the test variables being examined. Another approach is to provide subjects with a fixed-portion breakfast in an effort to standardize their appetite ahead of consuming the test meal of interest. To ensure that subjects arrive at
an eating trial in similar need states, most studies ask subjects to:

- fast for a fixed period of time before the test meal, often overnight;
- abstain from excessive physical activity the evening before a test meal;
- consume a fixed breakfast at a fixed time to equilibrate subject need state ahead of a lunchtime test session;
- follow their normal dietary behavior in the days around a meal study.

Differences in need state should be captured in any meal trial as baseline measures, where hunger, fullness, desire to eat, and often the time since the last meal are recorded for each participant. These measures can then be used to compare need state against energy intake and further controlled for in the analysis of energy intake across days. Large variations in subjective need state at the beginning of a given test session can confound the comparison of the experimental variables under investigation. These differences can be further controlled through the use of a crossover experimental design, which offers better control over individual differences in fullness and satiety as each individual subject acts as his or her own control.

Subjective differences in appetite ratings capture the perceived need state of an individual or group of individuals, but often these differences do not translate into differences in intermeal interval or later food intake. In this regard, if your ratings indicate you feel hungrier, you do not necessarily always eat more food. Appetite scales cannot be used as a substitute for a controlled eating behavior trial in which food intakes are accurately measured, as the relationship between food intake and perceived hunger is highly variable across subjects and based on energy consumed and the length of time after the treatment of each rating (De Graaf, 1993; Mattes, 1990; Yeomans & Bertenshaw, 2008). Appetite ratings made early or in the middle of the postmeal period are correlated more strongly with later food intake, whereas these differences become less important the longer after the meal the ratings are made (Gibbons, Finlayson, Dalton, Caudwell, & Blundell, 2014). To supplement subjective appetite ratings of satiety, behavioral satiety can be measured objectively as satiety duration by recording the time to the initiation of the next eating event and by recording the amount of energy consumed at the next meal.

### 3.4 Objective Measurement of Satiation and Satiety

To quantify satiation the experimenter should record the total ad libitum energy (kcal) consumed to fullness within a meal (Fig. 7.2(a)). To quantify satiety objectively it is necessary to measure the time to the next meal and/or the amount of energy consumed at the next meal (Fig. 7.2(b)–(d)). Measuring time to the next meal is based on the belief that energy intake homeostasis is maintained by eating frequency, and is applicable only when there is free choice on the time to the next meal for the subjects, and this timing can be accurately recorded in what is termed a “free satiety” paradigm. It is also neces-
sary to avoid having obvious visual cues, such as watches or clocks present in the test room, as this may lead to a reliance on habitual eating patterns rather than individual motivation to eat driving the intake behavior. It is more common to measure the amount of energy consumed at the next meal, and for this measure it is necessary to standardize the time between eating events. Satiety is a combination of both the duration of the feeling of fullness and the adjustments to energy intake at the next meal, so where possible it is advisable to record both.

A common approach to measuring the satiety response to a food is to serve the test treatment as a preload and record intake of energy at a meal following a predefined time gap (Fig. 7.2(c) and (d)). The preload test design is widely used to estimate the short-term satiety effect of a test treatment. To avoid interindividual variation in satiety responses, it is best to run preload studies as a within-subjects design and have all subjects complete all conditions. Using the preload paradigm, satiety is measured by measuring ad libitum energy consumed to satiation a fixed period of time after a test preload has been consumed, and then this response can be compared across treatments or benchmarked against a control condition (Blundell et al., 2010). The rationale behind the approach is that treatments that yield more satiety will lead to a reduction in ad libitum intake within a standard meal and vice versa (Fig. 7.2(c) and (d)). The key distinction between this approach and that taken for the measurement of satiation is that in a satiety test, the test treatment of interest presented before the ad libitum meal is the same across test treatments, and intake is measured using a standard meal. For a satiation trial the ad libitum meal is the test variable and the experimenter is interested in how intake changes across different variants of the ad libitum meal (see Fig. 7.2 for examples). To ensure the satiety measure is sensitive, the time gap between the preload treatment condition and the ad libitum meal must be strictly controlled. In a comprehensive review of preload studies, Almiron-Roig noted that participants tended to be worse at adjusting subsequent food intake as the energy density of the preload increased and as the hiatus between the preload and the test meal became longer (Almiron-Roig et al., 2013). Current best practice suggests there is maximum sensitivity to preload energy differences when this hiatus is kept to between 45 and 60 min and typically no longer than 90 min.

When quantifying satiety in this way it is necessary to measure the energy compensation for the amount consumed as a preload and compare this to a control preload condition. The percentage compensation for energy consumed as a preload can thus be calculated as:

\[
\text{Percentage compensation} = \frac{\text{[Energy intakepreload]} - \text{[Energy intakecurrent meal]}}{\text{[Energy intakepreload]} - \text{[Energy intakecurrent meal]} \times 100}
\]

For example, a control treatment could be the current version of the product of interest, whereas the treatment condition could be a reduced-energy version of the same product. An energy compensation score of 100% would indi-
cate perfect compensation for the amount of added or removed energy consumed as a preload treatment (i.e., preload is 200 kcal and the ad libitum meal is reduced by 200 kcal). However, energy compensation is rarely this accurate and numerous studies have documented the imprecision of short-term human energy intake control (Almiron-Roig et al., 2013; Levitsky, Obarzanek, Mrdjenovic, & Strupp, 2005; McCrickerd, Salleh, & Forde, 2016; Tey, Chia, & Forde, 2016). Changes in acute energy intake are not fully reflected in short-term changes in eating behavior, as when a given day's intake and expenditure are compared there is little association, until these are averaged over longer periods, such as weeks. Therefore small deficits or excesses in energy may not always be detected, as energy balance does not truly equilibrate until after extended periods of time (Hall et al., 2012; Westerterp, 2010). For these reasons, results from short-term studies should be interpreted cautiously. For greater sensitivity and discrimination in satiety responses to different treatments, it is useful to integrate physiological measures to capture changes in satiety biomarkers in the postmeal period (Allirot et al., 2014). These can provide insights into physiological changes underpinning the subjective experience of satiety and the behavioral satiety measure of later food intake. It is necessary to pair the appropriate experimental paradigm with the time course of suitable metabolic or endocrine correlates when attempting to understand the different physiological mechanisms that underpin eating behavior (Allirot et al., 2012). For example, premeal ghrelin levels are relevant to satiation, whereas postmeal phenomena such as gastric emptying rate; changes in circulating levels of certain gastrointestinal hormones such as glucagon-like-peptide-1 (GLP-1), peptide tyrosine tyrosine (PYY), cholecystokinin (CCK), and polypeptide-P (PP); and suppression of ghrelin are more relevant when exploring satiety (Delzenne et al., 2010). Similarly, across the gastrointestinal endocrine signals for satiety there are differential sensitivities to energy from protein, fat, and carbohydrate content.

Although the distinction between measuring satiation and satiety is clear, there are many aspects of study design that can affect appetite and eating responses to a test meal or treatment and influence outcomes for both sets of measures. These include sensory influences in the test foods, individual differences among participants, and a wide range of variables in the choice of test setup and location. The following section provides some guidance on experimental considerations when setting up an eating trial to measure satiation or satiety.
4 CONSIDERATIONS FOR SELECTING TEST STIMULI AND LOCATION

4.1 Selecting a Meal Paradigm and Test Meal

Whether measuring satiation or satiety, care should be taken to consider the most appropriate test foods to represent the test variables for the specific experimental question. Given the dominance of cognitive influences in subjective eating responses, where possible the underlying macronutrient and energy content of the test stimuli should be manipulated in real foods that mimic normal everyday meal consumption, rather than in model foods that do not reflect the normal eating context. In addition, manipulations of a test meal's energy or macronutrient content can be made covertly or overtly, where the subject is made aware of the differences. This awareness can influence the subjects' eating response, and so care must be taken when deciding whether this awareness will unduly influence the outcome of the trial (Stubbs et al., 2001).

The number and nature of test foods provided, their predominant sensory character and intensity, and their palatability are hugely influential in the calories consumed to satiation. When selecting the food for a test meal it is best to fix all of the other parameters of the meal and vary the test meal only on the property being tested. This requires strict control of the test food properties, including the food's sensory and hedonic properties, as strongly flavored or highly liked foods should be avoided in case they stimulate intake independently (Yeomans, 1998; Yeomans, Lee, Gray, & French, 2001). Palatability has been shown to influence the amount of energy consumed to satiation but not influence satiety (De Graaf et al., 1999). Often, other overlooked food properties can also influence the rate and amount consumed, including food texture (de Graaf, 2012) and the impact this has on eating rate (Forde, van Kuijk, Thaler, de Graaf, & Martin, 2013a) and overall energy intake (Bolhuis et al., 2014; Forde, van Kuijk, Thaler, de Graaf, & Martin, 2013b). A food's sensory properties play a functional role in moderating the way it is eaten and influence the total amount of food consumed within an ad libitum meal (Forde, 2016; Green, Wales, Lawton, & Blundell, 2000). For example, a longer orosensory duration and stronger sensory intensity are associated with faster onset of satiation (Bolhuis, Lakemond, de Wijk, Luning, & de Graaf, 2011; McCrickerd & Forde, 2016). Unless the study aims to explore the impact of sensory properties on energy intake, every effort should be made to avoid explicit sensory cues that signal differences in energy content, food textures that strongly influence eating microstructure, and strong flavors that will polarize preferences across participants or become aversive following repeated exposure.

Satiation and satiety studies have the option of using either a single-course ad libitum meal or a buffet-style ad libitum meal paradigm to measure intake.
When the goal of the trial is the measurement of total amount of energy consumed, it is recommended to use the single-course meal, as it is a reproducible and reliable measure of self-selected energy intake and normal eating behavior for the given test meal (Gregersen et al., 2008).

### 4.2 Single-Course Meal Paradigm

The single-course test meal can be used to measure both satiation (energy consumed to fullness) and later energy intake following a period of satiety (Fig. 7.2(a)–(d)). The single-course paradigm is the most widely used approach to quantifying the food consumed to fullness in response to the variable that is being tested. An advantage of the single-course meal is that it is easy to implement and interpret and enables a clear measure of quantitative intake to fullness that is well controlled for biases. A limitation of the single-course test meal approach is that when restricting consumption to a single meal item, the focus is only on quantity consumed and not on food choice, thus poorly reflecting a real-life meal where multiple food items are available and can be freely consumed (Chapelot, Blundell, & Bellisle, 2013; Hill, Rogers, & Blundell, 1995). Similarly there is a natural decline in food pleasantness associated with the continued consumption of the same food item that has been termed “sensory-specific satiety,” and the relative contribution of this to measured satiation cannot be accounted for separately in the results, as this may vary from person to person and as a function of the sensory properties of the food items served. In selecting the meal's predominant sensory properties, most ad libitum meals tend to be savory, though research has indicated that there is no difference in the onset of satiation for equally sweet or savory ad libitum meals (Griffioen-Roose, Mars, Finlayson, Blundell, & de Graaf, 2009). The food should have a medium energy density (1–1.5 kcal/g), as small differences in intake of a very energy dense meal may unrealistically overestimate the effect on total energy consumed. For the same reason, the food chosen should not be unusually high in a specific macronutrient, as high-fat meals have been found to inflate energy intake and do not generalize to everyday meal occasions (Green et al., 2000). The food chosen should not be unfamiliar, as intake may reflect a neophobic response rather than the true motivation to consume.

In addition to the sensory properties, food variety ought to be limited during an ad libitum test meal and held constant across all test sessions so as not to confound comparison of energy intakes and encourage additional intake due to “variety effects” (Hetherington, Foster, Newman, Anderson, & Norton, 2006). The foods chosen should also be appropriate for the consumption context under investigation, such as serving breakfast foods at a breakfast ad libitum trial and savory foods for lunch (Cardello & Schutz, 1996). One requirement is that participants receive an ample serving of food at the beginning of an ad libitum eating trial to prevent them from cognitively estimating how
much food they plan to consume at the outset of the meal. The term “ad libitum” refers to providing participants with free access to the food being measured and ensuring there is always a surplus of food served, meaning more food than a participant would be expected to consume. This is typically completed through the provision of a large portion of the test meal (800–1000 g) with the instruction that more is available if required. The reason for this is to reduce the risk of external cues that may influence some individuals' eating behavior, such as plate cleaning, where the participant is reliant on visual cues and not appetite motivational state when deciding to cease consumption (Fay et al., 2011; Hinton et al., 2013; Wansink & Johnson, 2015). One example of the overreliance on visual cues is the refilling soup bowl study, in which participants ate an average of 73% more energy when their bowls were covertly refilled, and yet reported not feeling significantly fuller (Wansink, Painter, & North, 2005). The same visual bias has also been found to influence satiety (Brunstrom et al., 2012). A criticism of serving large single-course ad libitum meals is that they are likely to tend to overestimate the amount of food someone would typically choose to consume because of the portion-size effect, whereby normal intake is inflated when larger portions are served (Diliberti, Bordi, Conklin, Roe, & Rolls, 2004; Rolls, Roe, Meengs, & Wall, 2004). Concerns have also been raised about using amorphous versus unit foods for the ad libitum test meals, as distinct food items presented as units may be subject to certain unit biases whereby participants tend to consume the whole item, rather than eating until comfortably full (Geier, Rozin, & Doros, 2006). Often this is dealt with by cutting larger units into smaller or more homogeneous sizes such as sandwiches that are cut into smaller pieces (Rolls et al., 2004). Despite suggested limitations, the single-course ad libitum test meal provides a reliable and reproducible measure of quantitative energy intake from a single meal when correctly applied (Arvaniti et al., 2000; Gregersen et al., 2008).

4.3 Buffet Meal Paradigm

An alternative is to present a buffet-style meal where multiple foods are presented in close proximity to participants and they can freely choose the type and amount of food they would like to consume (Allirot et al., 2012). When setting up a buffet-style meal, all items should be clearly identifiable and served in an individual bowl and subjects should be served a surplus that is more than they would be expected to consume. The main advantage of the buffet meal paradigm is the additional insight into the qualitative aspect of food choice as well as the quantitative information on energy intake during the same meal. Through careful selection of the test foods, the buffet meal makes it possible to study macronutrient selection under specific conditions and facilitate an understanding of the interplay between liking and homeostatic need state. Examples include studying macronutrient and energy selection following exercise (King & Blundell, 1995), or when testing whether food choice
and intake are manipulated when participants are significantly protein depleted (Griffioen-Roose et al., 2012).

Buffet-style meals add an additional parameter in food choice and selection, which may not reflect the homeostatic drive to eat but rather is motivated by a desire to consume a variety of hedonically appealing foods independent of need state (liking and wanting) (Berridge, 1996). The time taken to select foods from the buffet has also previously been reported as an indication of participants' motivation to eat (King, Burley, & Blundell, 1994) and a measure of their “food wanting.” The buffet meal confounds the direct causal measurement of food intake based on appetite motivational state alone, by adding additional dimensions to the measure. The broader inference derived has significant limitations in that conclusions regarding food choice and preference can be drawn only on the foods presented (Blundell et al., 2010; Chapelot et al., 2013). Strict control must be placed on the selection of foods and their presentation, as outcomes can be unintentionally biased by the arbitrary nature of the foods provided or even the proximity of the foods on the table in front of the participants. Energy intake can also be unduly influenced by differences in food temperature, energy density, or salient sensory properties. Buffet lunch meals also cause problems for repeated-measures (crossover) designs, as subjects tend to spontaneously choose different test foods across successive test days, which may confound interpretation of energy and macronutrient intakes as they relate to the test variables (Kissileff, 1985). In summary the single-course meal is appropriate when the focus is on measuring quantitative intake of energy or macronutrients and is often preferred when studying the biological determinants of food intake within and between meals (Karl, Young, & Montain, 2011). The buffet meal is suitable when studying food choice and intake simultaneously for specific experimental questions, but should be used judiciously as it is prone to greater variability, and reproducibility of the findings can be strongly influenced by the foods chosen.

Data from eating trials can only be as good as the rigor of the experimental paradigm selected for the test question being addressed, the test variables selected (i.e., foods or beverages), and the participants recruited to complete the tasks. Food intake trials are indirect measures that rely on control and consistency under the test conditions for inferences to be successfully drawn on the reasons for the initiation or cessation of an eating event. In addition to the selection of the appropriate test food and paradigm, the measurement of satiation requires consideration of other influences of food intake that can significantly influence the outcomes. These include the test location, instructions, participants, and design or setup. These are discussed in more detail next.

### 4.4 Measuring Food Intake in a Laboratory

Food intake trials can be conducted in an ingestive behavior laboratory or in a free living test environment. One test environment may be more or less suit-
able than another, depending on the goals of the trial being completed, as there is a trade-off to be made between control and accuracy of the measures compared to the ecological validity of the consumption context. These decisions represent the equilibrium between internal and external validity of the measures collected, and rather than one correct approach, a balance needs to be struck between the two when choosing the appropriate test location for a specific study. Laboratory studies enable direct comparison of specific factors on appetite and eating behaviors, and conclusions can be drawn from a trial only if there is sufficient control in the accuracy and precision of ratings and food intake measures taken during the trial. Every effort should be made to remove food-related cues from the test environment and standardize the test space for noises, clocks, smells, and potential distractions. When setting up a test to measure food intake, it is important to consider a range of factors that can significantly influence or bias the amount of energy consumed until fullness. These include environmental cues within the test room such as plate size, choice of utensils, visual cues that may stimulate appetite, background odors and noises, food label information, and consistency of the food stimuli. Every effort should be made to keep these factors controlled and constant from one session to the next to ensure comparable experimental conditions across stimuli.

Confidence in the results will be enhanced by a longer measurement period, as acute eating studies cannot be generalized to accurately represent habitual dietary energy intake behavior. Additional food intake measures can be collected away from the laboratory through the use of food diaries, though these tend to be cumbersome to complete and analyze and are regarded as limited because of widespread response biases and underreporting (Livingstone et al., 2000). When comparing eating trials conducted in a laboratory and in free living environments the differences extend beyond eating context, as different methods of data collection are applied to studies conducted in each setting. In addition, in recent years the eating environment itself has become a test variable, as many studies attempt to understand social and environmental factors that influence food intake (Robinson, Tobias, Shaw, Freeman, & Higgs, 2011; Stroebele & de Castro, 2004).

4.5 Remote Food Intake Data Collection

In addition to collecting food intake data in the laboratory it is also possible to gather estimates of energy intake remotely. Although there have been advances in the remote collection of dietary data and some efforts to validate meal photographs with nutritional information, remote data collection for energy intake is still widely regarded as inaccurate and at best an estimate of energy intake (Martin et al., 2009). Food purchase behavior has been tracked through food disappearance data, shopper loyalty cards, and scanner information (Mathias, Ng, & Popkin, 2015; Smith, Ng, & Popkin, 2014), and whereas
these data may provide macro-trends in population intake behaviors, they cannot provide reliable information on intake or motivational states and are unsuitable for studying satiation and satiety. When setting up an eating trial, there is an important trade-off to be made between the highly controlled internal validity of the laboratory and the lower control higher external validity of the external environment. Current methods for measuring eating behaviors and recording food intake away from the laboratory are less accurate than laboratory-based methods and the preference remains to study appetite and food intake in controlled laboratory trials designed to achieve representative data for causal inference (Gibbons et al., 2014). Short-term records of food intake can be recorded away from the laboratory to capture an estimate of the quantity and timing of additional food intake later the same day of an experimental treatment. An example is the use of food diaries to collect later snack or evening meal intake following the consumption of a test meal (for examples see McCrickerd et al., 2016; Tey et al., 2016). These food diaries can then be collected at the next session and entered by hand into diet analysis software to estimate the kilocalories and macronutrient intake away from the laboratory, and are added to the data for total energy consumption over the course of a test treatment day.

5 GENERAL GUIDELINES FOR SETTING UP A SATIATION OR SATIETY TEST

5.1 Selecting the Appropriate Test Participants

In addition to thoughtful consideration of food stimulus selection, equal attention should be given to the selection of a test population appropriately screened to ensure they are representative participants for the test being conducted. If the emphasis in the trial is to study the satiating properties of a new formulation or compare one product to another then it is often better to restrict the variability in the test population and recruit a homogeneous group of subjects (i.e., lean healthy males, within a narrow age range, and frequent users of the product). This would be the case when using a “satiety panel” to function much like a trained sensory panel, but to compare the filling properties of different foods from the same category (Lesdéma et al., 2016). A satiety panel comprising 15–18 subjects could be recruited to make satiety comparisons across products. Subjects tend to be matched for criteria that would be expected to influence food intake and subsequent feelings of hunger and fullness, such as body weight, gender, appetitive traits, and eating behaviors such as dietary restraint or usage of the product category. If the goal of the trial is to understand the consistency of the satiating properties of a product across a wide population, then the test subjects themselves become a focus of the eating trial and differences in the amount consumed to fullness or their subjective impressions of fullness over time can be compared across a large and diverse
cohort. For population-wide claims it is first important to consider whether the eating trial has been carried out in a group representative of the population group for which the product is intended. Studies in groups of specific populations beyond the general population (e.g., elderly subjects or subjects with a specific disease) must be assessed on a case-by-case basis for the extent to which the established satiety response can be extrapolated from the study group to the target group. Population-wide claims require specific power calculations to identify the appropriate sample population size and can be further enhanced through replication of the eating response of subjects to enable comparison of the satiating responses for subgroups (i.e., males and females, lean and obese, or subjects with different eating behavioral traits for the same foods).

5.2 Standardizing the Test Instructions to Participants

Seemingly straightforward differences in the instructions given to subjects at the beginning of a test meal can sometimes have unintended consequences on eating trial outcomes. For example, changing instructions from “eat until comfortably full” to “eat your normal lunchtime meal” can alter the eating goals of the subject and conceal subtle underlying differences in need state and change the outcome of the trial. Specific attention should be given to ensuring that the overall goals of the trial are protected from influences that will prevent comparison across the variables of interest post hoc. Similarly, making subjects aware of the time they will have to wait until their next eating event has been shown to significantly influence the amount of food consumed during an ad libitum test meal (De Graaf et al., 1999). Most trials fix the amount of time subjects are given to consume the test meal, rather than leaving it open ended for participants to decide, as this can also lead to response biases if subjects feel obliged to keep consuming until instructed to stop by the test instructor. Participants should be given a sufficient amount of time to eat a test meal and this should match the usual time needed to eat a meal of this nature.

5.3 Test Design and Power Calculation

When considering the outcomes and experimental comparison you would like to make in the data collected, there is a choice to be made between measuring differences between test products and treatments or differences between an individual's satiety responses. For studies that aim to explore individual differences in satiety response, the number of treatments should be limited, whereas a large number of participants are required (Appleton, Martins, & Morgan, 2011). Between groups (Forde et al., 2013b) and incomplete block designs (Viskaal-van Dongen, Kok, & de Graaf, 2011) have been used in the past, but owing to large interindividual variation in the study population, it is preferable that each subject receives all treatments in a repeated-measures/crossover de-
sign. With between-groups designs large numbers are often required to average out individual differences, and differences in food intake can be compared only at a group level. For preload satiety studies, some comparisons have highlighted differences in the sensitivity of crossover versus between-groups designs and found that crossover designs tend to underestimate energy compensation in satiety trials on sweeteners (Gadah, Brunstrom, & Rogers, 2016). For studies that aim to compare the satiating properties of foods the optimal approach is a repeated-measures design in which all subjects receive all treatments at least once and can act as their own control when comparing the effects of a treatment on hunger, fullness, and subsequent amount consumed. For these studies there is no published optimal number of treatments, but often it is best to keep the treatments to no more than five or six to avoid subject fatigue, dropouts, and potential learning from repeated exposure (Blundell et al., 2010). Each study should be accompanied by its own power calculation to ensure sufficient power across experimental treatments where the sensitivity of the test measures is determined by the measure being used (i.e., intake from a test meal is more sensitive compared to estimating intake from a food diary). Studies of this nature typically require no fewer than 20–25 subjects and often start with more (n = 30) to ensure sufficient comparisons can still be made should some subjects drop out. The study design should maximize the control and accuracy of the comparisons of interest within the specificities of the test population and treatments. Where possible, the sample size should be guided by power calculations based on previous measures of sensitivity and variance for a similar treatment and test population. The sensitivity required for the measures applied in an eating trial are influenced by the degree of difference in the food stimuli being tested, the homogeneity of the test population, and the number of treatments under investigation. For satiety trials, the degree of difference in the energy content of the treatments and the time difference between the preload and the test meal will also influence the sensitivity of the measures. Sensitivity to differences in the energy content of a preload decreases progressively the longer the hiatus between preload and test meal. Best practice would be to power the study to cover the least sensitive measure, ensuring all other measures are adequately covered.

6 ADDITIONAL MEASURES FROM SATIETY AND SATIATION TRIALS

6.1 Eating Microstructure and Food Intake

In addition to understanding how much food is consumed to satiation, it is also of value to study the kinetics of food intake during a meal to track the temporal development of satiation as it relates to eating patterns. These behaviors have been termed the “microstructural patterns of eating” and include a description of the total number of bites, average bite size, bite rate, chews per
bite, and average eating rate associated with eating different foods or as measured at different phases of the meal. Objective approaches for studying eating microstructure have been used for nearly 40 years and began with the development of the “Edogram” (Bellisle & Le Magnen, 1980) and later the “universal eating pattern monitor” (Kissileff, Klingsberg, & van Itallie, 1980). In both cases it is possible to track eating throughout the meal by measuring the changing weight of the plate as food is removed, using an electronic balance that is concealed within the table. Using these data it is possible to plot cumulative intake curves of grams consumed per minute, the slope of which is a measure of a participant's eating rate at different phases of the meal. Specific algorithms have been developed to compare cumulative intake curves across different types of participants and foods (Kissileff, Thornton, & Becker, 1982; Westerterp-Plantenga, 2000). It is also possible to track changes in appetite ratings sequentially throughout the meal and relate this back to the microstructure of eating to track whether changes in motivation to eat are reflected in certain eating styles (Yeomans, 2000). Using these approaches it is possible to track the patterns of intake within a test meal, or study the psychopathology of disordered eating behaviors (Ioakimidis et al., 2011; Zandian, Ioakimidis, Bergh, Brodin, & Södersten, 2009). In the latter case, an understanding of disordered eating microstructure has led to the development of intervention strategies based on eating rates to enhance the regulation of energy intake (Ford et al., 2010). Research has shown that participant awareness that their intake was being observed made little difference to either the amount consumed or the eating microstructure during a test meal (Robinson, Kersbergen, Brunstrom, & Field, 2014; Thomas, Dourish, & Higgs, 2013, 2015). One drawback with ingestive pattern monitors for tracking eating is that when using the covert approach up to 25% of the data can be lost because of errors such as leaving cutlery on the plate or on the balance (Thomas et al., 2015). An alternative approach is to use behavioral coding of video recordings of subjects eating during an ad libitum meal, and previous research has highlighted the validity of behavioral coding analysis of video recordings for use in quantifying eating behavior (Hennequin, Allison, Veyrune, Faye, & Peyron, 2005). These approaches provide important insights into the motivational state of subjects and individual differences in eating behaviors within a test meal that enable post hoc explanations of differences in energy intake or feelings of fullness (Ferriday et al., 2016). Using this approach it was possible for Bolhuis and colleagues to understand the impact of harder food textures on average bite size, orosensory exposure time, and eating rate that led to a 13% reduction in ad libitum food intake at a lunchtime meal (Bolhuis et al., 2014). Behavioral coding of eating behaviors has the advantage of being noninvasive, reliable, and cost effective, and can provide important insights into the microstructural patterns of eating within a meal to support satiation and satiety measures.
6.2 Measuring Expected Satiety

The starting point for all of the aforementioned satiation and satiety methods is the beginning of the meal, but many of the important calorie intake decisions that control food intake are often made before a meal begins, at the point of selecting the food (energy density) and the portion (energy content). Most people tend to consume all of the food they select to eat and “plate clean” (92%–97%), relying on this visual cue rather than physiological feedback within the meal to determine the amount of energy to consume (Wansink & Johnson, 2015). Similarly, we are rarely surprised by how full or hungry we feel at the end of the meal, and research indicates a certain degree of premeal planning occurs in which we mentally budget the amount of food to consume, to alleviate hunger for a desired period (Brunstrom, 2014; Fay et al., 2011). We have a broad experience of the filling properties of a wide range of different foods and this largely determines the portion we select for a given meal (Brunstrom & Rogers, 2009). Significant advances have been made in our understanding of the cognitive processes that inform food and portion selection before the meal and our understanding of the relationship between portion choice and postmeal satiety (Brunstrom, Shakeshaft, & Scott-Samuel, 2008). Much of this research has focused on the development of approaches to quantify consumer expectations of the fullness (expected satiation) and the absence of hunger between meals (expected satiety) that different food and beverage products are expected to deliver (Forde, Almiron-Roig, & Brunstrom, 2015). These perceptions can be reproducibly measured, can discriminate between foods and beverages, and have been shown to predict actual portion selection and intake at a later meal (Forde, Chia-Ming, Lim, Sim, Cheon, 2016; Wilkinson et al., 2012). A better understanding of the food properties that moderate expectations of fullness and satiety can provide valuable insights into human energy selection and intake behaviors and complement the satiation and satiety test meal approaches outlined earlier. Although these techniques cannot replace the sensitivity of experimentally measured food intake recorded in human eating trials, they make it possible to compare a wide range of food product variables for the impact they are likely to have on portion selection and satiety expectations. An example is a 2015 study that applied these measures to gain a better understanding of how protein addition influenced expectations of fullness across a series of yogurt samples (Morell, Piquer-Fiszman, Hernando, & Fiszman, 2015). In this regard, expected satiety methods complement traditional satiation and satiety eating trials by enhancing our understanding of the motivations behind energy selection and intake, and by providing guidance on the appropriate portion size required to satisfy hunger.
7 LINKING BEHAVIORAL MEASURES OF SATIETY TO PHYSIOLOGICAL CONSEQUENCES OF FOOD INTAKE

This chapter describes the subjective measurement of appetite and energy intake to satiation and subsequent quantification of satiety. These subjective feelings and behaviors are causally driven by changes in our neural, endocrine, gastric, and gastrointestinal responses to the foods consumed. It is possible to connect physiological measures of satiation and satiety with the eating trial measures outlined earlier. These physiological biomarkers are typically collected using repeated-measures designs whereby each participant can act as his or her own control and changes from baseline across treatments can be compared for each individual. When quantifying the post-ingestive physiological response to a test food or beverage the changes in concentration of gastric or serum biomarkers will be dose-dependent, so it is important to standardize the portion served for the test food for consistency of comparison. The most commonly reported physiological measures tend to be signals from the stomach and endocrine signals from both the stomach and the gastrointestinal (GI) tract that act directly on the brain or peripherally on the central nervous system (Cummings & Overduin, 2007). These targets include changes in gastric distention, gastric emptying, and secretion of endocrine peptides in the stomach and GI tract. Gastric distention and emptying can be measured using ultrasonography or MRI and by the rate of paracetamol absorption, which is used for liquids. These measures increase respondent burden and tend to be conducted in parallel to rather than within eating trials, to compare gastric distention and rate of gastric emptying across several foods. There are also a number of widely studied biochemical targets that are linked to the onset and decay of satiation and satiety, and these are predominantly peptide hormones that either stimulate appetite (orexigenic) or suppress appetite (anorexic). These “satiety peptides” are secreted into the stomach, ileum, and GI tract and can act either centrally in brain regions such as the hypothalamus or peripherally to mediate neuron activity, or both. The chosen biomarker of satiation and satiety needs to be reliable, sensitive, specific, and predictive of appetite feelings and food intake (de Graaf, Blom, Smeets, Stafleu, Hendriks, 2004). The most common targets include the appetite-stimulating hormone ghrelin (orexigenic) and the anorexigenic hormones CCK, GLP-1, and PYY (Delzenne et al., 2010). PP has also been studied in relation to the sensory and nutrient content of beverages (Yeomans, Re, Wickham, Lundholm, & Chambers, 2016). The glycemic response to food intake can also be profiled by measuring changes in circulating blood glucose and secretion of the peptide hormone insulin, and meal initiation has been linked to declines in blood glucose (Kovacs et al., 2002).

Serum concentrations of the target satiety peptide are collected in tandem with food intake and satiety ratings using sequential blood draws at time
points that overlap with subjective appetite ratings (see Yeomans et al., 2016, for an example). These peptides differ in their detection sensitivity and time course and are secreted differentially in response to different foods and sensory stimuli. The choice of which peptide target to measure is contingent on the research question being asked and the macronutrient content of the foods under investigation, and studies have suggested combinations of peptides for maximum sensitivity (Mars et al., 2012). Measuring these peptides makes it possible to explore aspects of the mechanism of satiation onset and satiety duration by tracking serum concentration changes for the chosen target peptides before, during, and after a test meal (Delzenne et al., 2010). These approaches allow comparing across test foods or new formulations, by tracking the same appetite and GI biomarkers under the same conditions across multiple test sessions, to identify the specific endocrine or gastric signals associated with the perceived differences in fullness. These physiological measures of satiety provide powerful insights into the mechanism underpinning differences in the satiety experience across foods. However, reproducible results from these clinical measures require invasive techniques such as cannulation for repeated blood draws, and the test procedure often adds further restrictions around eating occasions to aid reproducibility and discrimination. These tighter restrictions may lead to a loss of ecological validity and may not truly reflect consumers’ real-life experiences with a test meal. For research purposes these controlled clinical approaches to understanding appetite regulation significantly aid our understanding of the neuroendocrine regulation of food intake, and provide detailed information on the cephalic, gastric, and GI impact of appetite.

8 CONCLUDING REMARKS

In recent years there has been an increased focus on understanding the satiating properties of foods and beverages and on developing approaches to communicate enhanced satiety as a functional benefit to an increasingly health-conscious consumer. Claims on functional benefits such as enhanced satiety or “feeling fuller for longer” are tightly regulated and must be supported with robust data that demonstrate a sustained effect in human eating trials (Halford & Harrold, 2012; Hetherington et al., 2013). Among food researchers there is an interest in using food formulation, structure, oral processing, and sensory properties to enhance the satiating power of foods per kilocalorie consumed (Campbell, Wagoner, & Foegeding, 2016; Chambers, McCrickerd, & Yeomans, 2015). There is an increasing awareness among food developers and consumer scientists that increasing the hedonic appeal of a food is no longer enough to sustain acceptance, and beyond the role in driving food liking, a food's sensory properties can strongly influence food choice and energy intake decisions (McCrickerd & Forde, 2016). The important distinction between the measurement of satiation (fullness) and that of satiety (fullness over time) is
critical when considering the experimental question being investigated in an eating trial, as each requires specific controls and measurement criteria. Accurately quantifying satiation and satiety sensations is central to progressing our understanding of the human psychobiology of eating behavior, energy selection, and intake. The techniques described in this chapter provide a framework for designing trials that enable the comparison of feelings of satiation and satiety for different products and across populations. For all such trials, consideration should be given to the test stimuli and the variables they represent and the test population from whom measures are derived, and care should be taken to design an approach that maximizes the sensitivity of comparison for the sensations of interest. Increasingly it will be necessary to go beyond simply tasting foods for sensory or hedonic appraisal, to understanding the development of fullness feelings within the product experience and their impact on energy intake regulation from meal to meal.

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