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Research report

Mechanisms of the portion size effect. What is known and where do we go from here? ☆

Laural English [a], Marlou Lasschuijt [a,b], Kathleen L. Keller [a,c,*]

[a] Department of Nutritional Sciences, The Pennsylvania State University, University Park, PA 16802, United States
[b] Division of Human Nutrition, Wageningen University, Wageningen, Netherlands
[c] Department of Food Science, The Pennsylvania State University, University Park, PA 16802, United States

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ABSTRACT

Childhood obesity is a persistent problem worldwide, and of particular concern in the United States. Clarifying the role of the food environment in promoting overeating is an important step toward reducing the prevalence of obesity. One potential contributor to the obesity epidemic is the increased portion sizes of foods commonly served. Portion sizes of foods served both at home and away from home have dramatically increased over the past 40 years. Consistently, short-term studies have demonstrated that increasing portion size leads to increased food intake in adults and children, a phenomenon known as the portion size effect. However, the mechanisms underlying this effect are poorly understood. Understanding these mechanisms could assist in clarifying the relationship between portion size and weight status and help inform the development of effective obesity interventions. First, we review the role of visual cues, such as plate size, unit, and utensil size as a potential moderator of the portion size effect. In addition, we discuss meal microstructure components including bite size, rate, and frequency, as these may be altered in response to different portion sizes. We also review theories that implicate post-ingestive, flavor-nutrient learning as a key moderator of the portion size effect. Furthermore, we present preliminary data from an ongoing study that is applying neuroimaging to better understand these mechanisms and identify modifiable child characteristics that could be targeted in obesity interventions. Our tentative findings suggest that individual differences in cognitive (e.g. loss of control eating) and neural responses to food cues may be critical in understanding the mechanisms of the portion size effect. To advance this research area, studies that integrate measures of individual subject-level differences with assessment of food-related characteristics are needed.

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Introduction

Obesity is a worldwide public health crisis (Ogden, Carroll, Kit, & Flegal, 2014) (Kelly, Yang, Chen, Reynolds, & He, 2008). In the United States, more than 30% of adults and 17% of children are obese, putting them at increased risk for the development coronary heart disease, type 2 diabetes, certain types of cancer, as well as low self-esteem and depression (Daniels, 2006; Miller et al., 2014). Obesity and its related comorbidities have an enormous economic impact on the health care system. In US adults, the national medical care costs of obesity-related illnesses are estimated to be over $209 billion per year (Cawley & Meyerhoefer, 2012). These costs are expected to increase by $66 billion annually by 2030 (Wang, McPherson, Marsh, Gortmaker, & Brown, 2011). In order to reverse these adverse consequences, strategies are needed to help individuals better regulate their energy intake in the face of widespread availability of highly palatable, energy dense foods.

One component of the food environment that has been attributed to excess energy intake is increased portion size of foods commonly served (Nielsen, 2003; Piernas & Popkin, 2011; Rozin, Kabnick, Pete, Fischler, & Shields, 2003; Young & Nestle, 2002, 2012). This trend started in the 1970s and persists today (Young & Nestle, 2012). Numerous short-term laboratory studies demonstrate that increasing portion size leads to increased energy intake in both adults (Kral & Rolls, 2004; Rolls, Morris, & Roe, 2002; Rolls, Roe, Kral, Meengs, & Wall, 2004; Rolls, Roe, & Meengs, 2006, 2007; Zlatevska, Dubelaar, & Holden, 2012) and children over the age of 3 years (Fisher, Arreola, Birch, & Rolls, 2007; Fisher & Kral, 2008; Fisher, Liu, Birch, & Rolls, 2007; Kelly et al., 2009; Mathias et al., 2012; Orlet Fisher, Rolls, & Birch, 2003; Rolls, Engell, & Birch, 2000). This has

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* Corresponding author.
E-mail address: kk2092@columbia.edu (K. Keller).

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been termed the "portion size effect" or portion size response. The effect has been observed with packaged snacks (Rolls, Roe, Kral, et al., 2004), energy dense casseroles (Orlet Fisher et al., 2003; Rolls et al., 2002), unit foods like sandwiches (Rolls, Roe, Meengs, & Wall, 2004), beverages (Flood, Roe, & Rolls, 2006) and even with low-energy dense foods like fruits and vegetables (Kral, Kabay, Roe, & Rolls, 2010). Additionally, the portion size effect has been demonstrated in more naturalistic environments like restaurants and offices (Diliberti, Bordi, Conklin, Roe, & Rolls, 2004; Geier, Rozin, & Doros, 2006). It has been observed even under conditions when participants are served unpalatable foods (Wansink & Kim, 2005) or when they are blinded to the portion size manipulations (Burger, Fisher, & Johnson, 2011; Wansink, Painter, & North, 2005). These studies demonstrate that the portion size effect is robustly observed across a variety of food types, environmental conditions, and study populations.

Despite the consistency of the portion size response across studies, the mechanisms underlying the effect are poorly understood. The purpose of this paper is to discuss relevant theories and evidence to help clarify the portion size effect. Because a majority of the studies have been done in adults, it is critically important to determine the extent to which findings can be generalized to different age groups. Little is known about how individual differences in response to portion size change over time, and further, how these changes relate to obesity. A clearer understanding of the mechanisms underlying how changes in portion size influence intake could inform the development of more effective obesity interventions. This is particularly important at a time when interventions are being tested to determine the effect of reducing portion size (French, Epstein, Jeffery, Blundell, & Wardle, 2012) and plate size (Robinson et al., 2014) on body weight. We argue that a clearer understanding of *why* and *how* portion size impacts energy intake is needed to ensure that these interventions are designed effectively. Burger, Fisher, et al. (2011) outline two possibilities that are used to guide the presentation of the literature. First, they propose that the portion size effect is an intuitive, cognitive process where the amount of food served acts as a visual cue to influence the amount ingested. Second, they alternatively suggest that the portion size effect could be a passive mechanical process where the physical amount of food available affects a person's eating behavior directly through alterations in bite size and frequency. A third possible mechanism has been proposed by Hardman, McCrickerd, and Brunstrom (2011) who argue that previous experience plays a key role in determining expectations about how filling a food will be, and consequently, might play a critical role in the portion size effect. Therefore, the amount consumed when presented with a portion could be the result of previous experiences with a food to learn its post-ingestive consequences. Yet a fourth possibility is that large portions of food activate the brain's reward and motivation pathways, and therefore drive consumers to eat more compared to smaller portions. In order to test these hypotheses and in particular, to examine the importance of reward pathways in driving the portion size effect, we close the review with preliminary findings from an ongoing study that uses neuroimaging to elucidate potential mechanisms in children.

Justification for understanding the portion size effect

Because the portion size effect has been consistently observed under a variety of conditions, one might question whether understanding its mechanism is important. Perhaps this response is a trait common to most humans, and therefore, is understanding *why* really important? We propose two key reasons for understanding the mechanisms underlying this response. The first reason would be if there is convincing evidence that the strength of the portion size response varies across either individuals or experimental conditions. If individual characteristics can be identified that lead some individuals to be more susceptible to increases in portion size than others, clarifying the mechanism of the portion size effect might help identify more effective approaches to dietary management of obesity. Depending on the mechanisms discovered, these approaches could range from targeting specific neural pathways involved with portion size perception to developing behavioral strategies to reduce food-cue exposure. With respect to individual differences in portion size response, a recent meta-analysis of multiple laboratory studies reported that while the average increase in intake with a doubling in portion size was approximately 35%, the strength of the effect across studies is not consistent. As the size of the portion served becomes larger, the portion size effect decreases (Zlatevska, Dubelaar, & Holden, 2014). Other factors might also impact the strength of the portion size effect. For example, energy density, a measure of the food's energy (kcals) per gram, has been found to influence intake, and its effects are thought to be additive to those of portion size. Children consumed 34% more energy at a meal when entrée-portion size alone was increased, but when *both* entrée portion size and energy density were increased, 76% more energy was consumed compared to reference conditions (Fisher, Liu, et al., 2007). Another factor that might impact susceptibility to the portion size effect is age. Studies find greater portion size effects in older compared to younger children (Orlet Fisher et al., 2003; Piernas & Popkin, 2011), which supports the theory that young children are better able to regulate their energy intake and are not as responsive to portion size manipulations (Birch & Deysher, 1986; Rolls et al., 2000). In addition to age, body weight has also been hypothesized to be associated with susceptibility to the portion size effect, but this relationship has not been consistently observed. While Burger and colleagues reported that overweight adults showed greater increases in intake from larger versus smaller portions of pasta compared to lean adults (Burger, Kern, & Coleman, 2007), most studies in adults have found no association between weight status and the portion size effect (Brunstrom, Rogers, Pothos, Calitri, & Tapper, 2008; Fisher, Arreola, et al., 2007; Rolls et al., 2002). However, several studies have reported variations in the portion size effect that are related to weight and/or appetitive traits in children (Fisher, Zakeri, Birch, & Kral, 2012; Sharafi, Fisher, & Birch, 2009). In addition, Kral, Remiker, Strutz, and Moore (2014) reported a trend for greater portion size responsiveness in overweight children. Because of these inconsistencies, additional studies are needed to clarify the impact of individual characteristics like weight status on susceptibility to portion size.

The second reason to understand the mechanisms underlying portion size relates to its potential impact on treatment. As previously mentioned, several recent clinical trials have included variations in portion size (French et al., 2014) or plate size (Robinson et al., 2013) as a potential treatment for obesity. The study by Robinson et al. (2013) is ongoing, but French et al. (2014) found that adults randomized to conditions where they received large portions (1600 kcals) of a boxed lunch gained weight and increased energy intake over a 6-month period, but those who received small portions (400 kcals) did *not* lose weight or eat less (French et al., 2014). These findings call into question common dietary advice to reduce portion sizes in order to lose weight, but additional studies under free-living conditions are needed before portion control strategies can be discounted. A clearer understanding of how portion size impacts energy intake could improve the effectiveness of these interventions. For example, if we are vulnerable to manipulations in portion size because of the added value they bring, interventions that eliminate this additional value by altering prices might be helpful (Harnack et al., 2008; Steenhuis & Vermeer, 2009; Vermeer, Steenhuis, Leeuwis, Heymans, & Seidell, 2011). If susceptibility to the portion size effect is due to an inability to correctly judge the amount of food served, interventions that reduce plate and bowl size to make foods appear larger might be effective.

Alternatively, if portion size acts as a visual cue that alters our meal intake behavior (ie. bite size, bite frequency), reducing the size of utensils might be the most effective approach. Given that both individual variations in the portion size effect and the mechanisms that underlie it could influence the success of treatments, additional investigation to clarify this research area is needed.

Mechanisms of the *portion size effect*

Amount of food as a visual cue that impacts the amount consumed

Visual cues are an important part of the overall eating experience that influence food choice and intake (Reisfelt, Gabrielson, Aasylng, Bjerre, & Moller, 2009). The color (Dubose, Cardello, & Maller, 1980; Koch & Koch, 2003; Spence, Levitan, Shankar, & Zampini, 2010), shape, (Olsen, Ritz, Kramer, & Møller, 2012; Reisfelt et al., 2009), and size (Wansink, van Ittersum, & Painter, 2006) all influence food acceptance and intake. Therefore, it is possible that portion size influences the amount eaten by providing visual reference for the amount of food available throughout the meal. In this section, we review evidence that suggests that portion size serves as an important visual cue that affects subsequent cognitive processes related to intake. We have focused this section on three areas of research: (1) plate size, (2) package and/or unit size, and (3) anchoring and adjustment.

Dishware size

The importance of visual cues to the portion size effect can be illustrated by experiments that have altered the ability to accurately perceive the size or shape of the portion of food served. Research has applied theories from the Delboeuf illusion, which is a visual illusion based on the perceived size of one object related to another. For example, one medium-sized circle appears smaller next to a larger circle, but the same circle is perceived as larger when placed next to smaller circles (see Fig. 1a) (Irvine, Brunstrom, Gee, & Rogers, 2013). Because of this, identical quantities of food would appear larger when served on a small plate but smaller when served on a larger plate (see Fig. 1b). By this theory, the size of the serving vessel could be one mechanism by which portion size determines the amount eaten because it affects the perception of the amount available. In addition, larger serving vessels also allow for more food to be served, and this could drive increases in energy intake. For example, taller, thin glasses are perceived to contain more liquid than shorter, broad glasses because adults and children use height as a cue to estimate liquid amounts (van Kleef, Shimizu, & Wansink, 2012; Wansink et al., 2005). Furthermore, adults tend to serve themselves more food on larger plates/bowls than on smaller plates/bowls (Wansink, 2006; Wansink & van Ittersum, 2003). Therefore, it is reasonable to hypothesize that the portion size effect might be partly due to the relationship between the amount of food present and the size of the plate or bowl on which it is served. As a result, reducing plate size while keeping portion size constant might lead consumers to conclude that they have consumed more food than they actually have and result in a reduction in intake.

While the literature has generally shown that smaller dishes reduce our perceptions of portion size, this does not always translate to reduced intake. While some studies in adults (Wansink & van Ittersum, 2013) and children (DiSantis et al., 2013) (van Ittersum & Wansink, 2007) found that plate/bowl size influenced the amount consumed, other studies dispute these findings (Koh & Pliner, 2009; Penaforte et al., 2014; Rolls, Roe, Halverson, & Meengs, 2007; Shah, Schroeder, Winn, & Adams-Huet, 2011; Yip, Wiessing, Budgett, & Poppitt, 2013). As an example, when given smaller plates, Rolls and colleagues found that adults made additional trips back to the buffet to compensate (Rolls, Roe, Halverson, et al., 2007). However, generalization across plate size studies is a challenge due to variations in the size and type of dishware, the size of eating utensils, and whether or not participants were allowed to serve themselves or were provided with pre-portioned test-meals. Robinson and colleagues published a meta-analysis on the available studies that had tested the impact of dishware size on energy intake and concluded that there was a small, positive relationship between plate size and amount eaten. However, studies were inconsistent and additional research is needed to better understand the impact of varying plate size on intake before effectively translating these findings to the general public (Robinson et al., 2014).

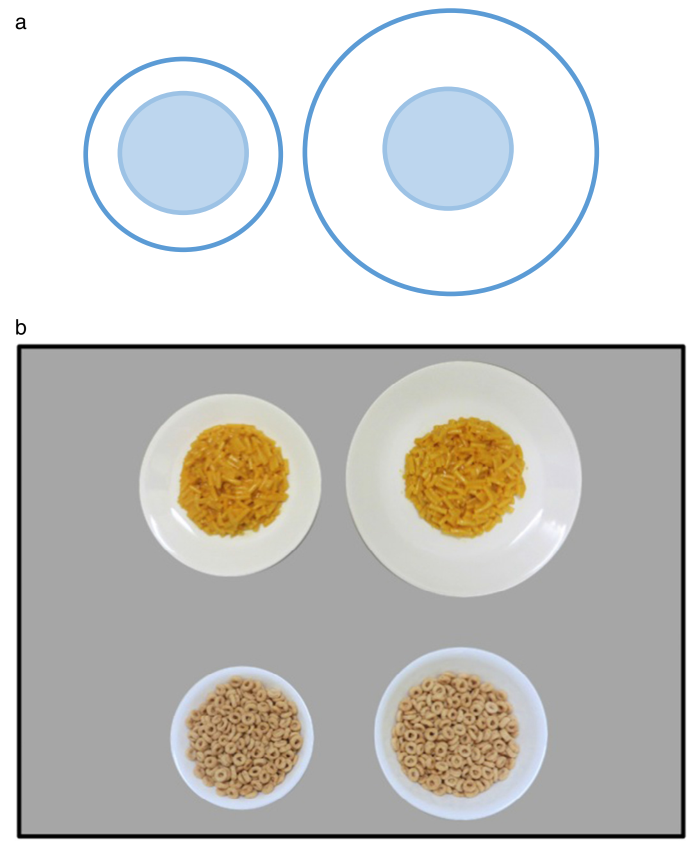

Fig. 1. a. Delboeuf illusion shown with concentric circles. b. Delboeuf illusion shown with actual foods (macaroni and cheese and cereal).

Some investigators have questioned what might happen to portion size susceptibility if visual cues are removed from eating. Wansink et al. (2005) compared intake of adults consuming soup from a normal bowl compared to a bowl that was covertly refilled as the soup was consumed. Adults with the refillable bowl ate 73% more soup compared to those in the non-refillable bowl condition, even though satiety ratings in both groups were similar (Wansink et al., 2005). Brunstrom and colleagues used refillable soup bowls to investigate appetite regulation and the effect of memory recall on expected satiation (Brunstrom et al., 2012), but found contrasting results to findings from Wansink et al. (2005). Adults who consumed the smaller portion perceived greater satiety only if they had been shown the larger portion prior to consumption. This suggests an important role for cognition on susceptibility to the portion size effect (Brunstrom et al., 2012). Despite this, Burger et al. found that blindfolding adults and exposing them to large and small portions of pasta did not reduce the portion size effect. Participants ate less in the blindfolded condition than when they could see, but irrespective of blindfolding, they were still susceptible to the portion size effect and showed increased intake of the larger portion (Burger, Fisher, et al., 2011). While these findings are informative in determining the underlying mechanisms, using blindfolds in a free living setting would likely not be a practical approach to reducing intake from large portions.

Overall, visual cues seem to be an important mediator of the portion size effect. However, visual perceptions are easily biased through plate/bowl or spoon size, and this can affect our ability to judge amount consumed. Whether this impacts actual intake is still unclear. These types of visual manipulations are more easily accomplished in laboratory-based feeding studies. However, in free-living conditions, portion size is often partially pre-determined by the package or container size in which food is sold (Marchiori, Corneille, & Klein, 2012). The extent to which laboratory findings on the role of visual cues on the portion size effect generalize to free living conditions remains to be tested.

Unit, package, and container size

The amount consumed from a portion of food can also be influenced through another visual cue, unit size. Unit size can be defined by a food's packaging or the size of the food product itself. Regardless of the portion of food it contains, the size of the package seems to be an important determinant of the amount of food consumed. Geier and colleagues term this "unit bias" (Geier et al., 2006). Adults consumed 129% more candies from larger containers than they did from smaller containers, despite the fact that the amount of M&Ms served was identical (Marchiori, Waroquier, & Klein, 2011). Rolls and colleagues found that adult participants given varied amounts of potato chips (28 grams vs. 170 grams) on separate days increased their snack intake with increasing package size (Rolls, Roe, Kral, et al., 2004). These studies show that container or package size plays a key role in our ability to estimate the amount of food and ultimately affects intake (Madzharov & Block, 2010). Given the increasing availability of "bulk" sized foods and "supersize" portions in the US (Scisco, Blades, Zielinski, & Muth, 2012), unit size may impact energy intake by influencing socially acceptable consumption norms. When consumers purchase a king size candy bar, they are highly likely to consume the entire bar at once because it is perceived as a single serving, regardless of the fact that the package actually contains 3 servings.

The impact of changing a food's unit size on intake has been studied by several laboratories, but the findings are inconsistent. In one study, adults ate more when served 10 large candies compared to when they were served the same amount of candies cut into 20 bite-sized pieces (Marchiori et al., 2011). These results are supported by another study that found that adult participants ate significantly more, and ate faster, when served 96 grams in the form of 6 large candy bars compared to when they were served the same amount of candy bars cut into 66 smaller pieces (Weijzen, Liem, Zandstra, & de Graaf, 2008). Conversely, Devitt and Mattes (2004) compared intake of small food unit sizes with intake of typical food unit sizes in adults and did not find a difference in intake or perceived fullness (Devitt & Mattes, 2004). Also, in a study with healthy-weight adults, Rolls, Rowe, and Rolls (1982) served one sandwich that was cut into either 2, 4, or 6 sections. Regardless of the number of pieces served, participants ate a consistent amount across condition (Rolls, Rowe, & Rolls, 1982). The distinction between cutting food in smaller pieces to decrease unit size (i.e. slicing a candy bar into smaller sections) or serving a smaller unit size as a whole (i.e. serving mini-candy bars) makes generalizing across studies difficult. Most studies on this topic have been performed in adults with sparse examination of the effects of packaging and unit size in children. Because of the popularity of unit foods among children's cuisine (e.g. french fries, chicken nuggets, squeezable yogurts), additional studies to clarify the impact of unit size and shape on intake in children are needed.

Studies that have manipulated food unit size to determine the impact on our perceptions of food amount shed additional light on the portion size effect. Both the size and number of food pieces influence our estimation of how much food is present in a particular serving. In a study by Wada, Tsuzuki, Kobayashi, Hayakawa, and Kohyama (2007) adults overestimated the amount of food in pictures of carrots that were cut into fine strips compared to pictures of many small cubes or 1 large cube of carrot. This suggests that the volume or total space occupied by a food affects our ability to estimate the amount correctly (Wada et al., 2007). Based on a recent review of such results, varying number of pieces can affect both quantity estimate and the amount consumed (Wadhera & Capaldi-Phillips, 2014). Presenting more pieces of foods (i.e. pretzels and flavored gelatin) while holding the amount constant led to an overestimation of the amount of food present in two separate studies (Madzharov & Block, 2010; Scisco et al., 2012). In general, food unit size, shape, number, and total volume occupied all appear to have some influence on our perceptions of the amount of food present, and possibly intake, but additional research is needed to understand how these factors interact with one another.

Anchoring, adjustment and consumption norms

An additional way in which portion size might serve as a visual cue to influence intake is through its ability to act as an anchor upon which appropriate levels of consumption are based. When an individual is presented with a typical eating situation, the size of the portion served might act as a reference point for how much should be consumed. The process of anchoring and adjustment as a heuristic – or mental short-cut – for how decisions are made when presented with limited information was originally discussed by Tversky & Kahneman (1974). It suggests that decisions are influenced by arbitrary or random anchors that affect judgments, and that when presented with an initial value, consumers adjust their perceptions based on this value to arrive at a final decision (Tversky & Kahneman, 1974).

Marchiori and colleagues hypothesized that the portion size effect might partially be explained by this notion of anchoring and adjustment (Marchiori, Papies, & Klein, 2014). Eating occasions might be especially vulnerable to anchoring bias because of the elastic nature of meal size (Hetherington, 2007) and the fact that internal satiety cues can readily be overwhelmed by social, cultural, and environmental influences (De Castro, 1996). Thus the portion size might serve as an important anchor to help us determine how much would be appropriate to consume (Herman & Polivy, 2008; Kral, 2006). Marchiori, et al., (2014) tested this by having adult participants imagine being served either small (low anchor) or large (high anchor) portions of food at a hypothetical lunch or snack followed by reporting how much of the food they would consume. As hypothesized, those who were given the low anchor portion reported they would consume less than those given the high anchor (Marchiori et al., 2014). These findings suggest that the portion size presented might serve as an anchor that affects judgments about what is an appropriate amount to consume. It remains to be tested if anchoring bias also influences the amount consumed from a portion, or if children are vulnerable to the same heuristic.

Portion size as a physical cue that alters meal microstructure

Although visual cues may be important determinants of the portion size effect, physical presence of amount of food available might result in changes in the microstructure of the meal that influence total intake. Several investigators have taken a microstructural approach to studying eating behavior to understand the impact of factors such as number of bites, bite rate, chews, licks, and patterns of mouth movement on total energy intake (Kissileff & Guss, 2001). Early work examined some of these behavioral components with automated liquid dispensers (Jordan, 1966) and solid food eating monitors (Kissileff, Klingsberg, & Van Itallie, 1980) to obtain cumulative energy intake curves over time. The relationship between variations in food portion size and meal microstructure has received little attention, but the few studies that have examined this relationship are reviewed in the following section.

Alterations in bite size, rate, and frequency

The question of whether the amount of food served alters meal microstructure has been of interest for over 50 years (Epstein, Parker, McCoy, & McGee, 1976; Ferster, Nurnberger, & Levitt, 1996; Mahoney, 1975). Spiegel and colleagues found that adult women slowed eating rate when served tuna, turkey, or bagels with cream cheese in large (15 gram) compared to small (5 gram) bites, but these relationships did not differ by participant weight status (Spiegel, Kaplan, Tomassini, & Stellar, 1993). This finding refutes mainstream beliefs that eating more slowly reduces energy intake, but does not clarify how a person would change the size of their bite or eating rate if given amorphous foods, like casseroles or pasta. Additionally, this study only examined women and gave them savory, energy-dense foods, but did not consider other food types such as fruits, vegetables, sweets or sweet-fats.

Others have investigated the role of portion size manipulations on bite size. Burger and colleagues gave adults small and large portions of a cheese pasta dish and found that bite size increased in the larger condition, regardless of whether participants were blindfolded to the manipulation, or if they could see the food (Burger, Fisher, et al., 2011). In children, Orlet Fisher et al. found that average bite size was significantly larger when 3- to 5-year-old children were given larger compared to smaller servings of macaroni and cheese. In addition, regardless of portion size served, heavier children tended to take larger bites than children with lower body weights (Orlet Fisher et al., 2003). In a follow-up study with children by the same group, similar increases were found in bite size with larger portions but there was no association with child weight status (Fisher, 2007). Interestingly, neither of these studies (Fisher, 2007; Orlet Fisher et al., 2003) found differences in bite frequency across portion size conditions. In addition, a related study where eating rate in adolescents was purposely slowed by serving a fast food meal in small, timed portions versus serving the same meal all at once found no differences in intake between conditions. The high palatability of the fast food meal was hypothesized to override any potential effects of the slowed eating rate on satiety (De Castro, 1996). This evidence suggests that while portion size might influence bite size, it does not appear to impact eating rate or overall bite frequency.

Portion size effect as a learned response

Work from Brunstrom and colleagues (Brunstrom, Collingwood, & Rogers, 2010; Brunstrom & Rogers, 2009; Hardman et al., 2011; Irvine et al., 2013) suggests that learning plays an important role in determining how much we plan to eat of a particular food on any given occasion. Therefore, previous experience with a food might predict the response to manipulations in portion size. In support of this, adults selected larger portions of foods to consume if they expected them to be less satiating (Brunstrom & Rogers, 2009). In order to measure how filling one expects a food to be, Brunstrom and colleagues have developed procedures for measuring expected satiety and expected satiation (Brunstrom & Rogers, 2009). Expected satiation is defined as the feeling of fullness one expects a food to deliver, while expected satiety is the extent to which a food is expected to prevent hunger after consumption is finished. Expected satiation can be assessed by having participants view pictures of foods and rate how filling they expect the foods to be (Hardman et al., 2011). In other studies, expected satiation has been measured by having participants taste small samples of food and rate how much fullness they expect the foods to deliver (Brunstrom et al., 2010). Expected satiety is typically measured by having participants rate how long they expect a food to prevent the onset of hunger in relation to comparison foods of known energy content (Brunstrom & Rogers, 2009). Regardless of the method used, it is important to point out that expected satiation is different from actual consumption, and therefore connections to the portion size effect are speculative.

Several factors have been found to influence ratings of expected satiation. For example, the macronutrient content (de Graaf, Stafleu, Staal, & Wijne, 1992), energy density (Brunstrom et al., 2010) and familiarity (Hardman et al., 2011) of a food have all been shown to impact how satiating participants expect the food to be. The presumed mechanism behind familiarity is a developed association between taste characteristics of a food and the post-ingestive events called 'flavor- nutrient learning' (Brunstrom, Shakeshaft, & Scott-Samuel, 2008; Wilkinson et al., 2012; Yeomans, 2012). Flavor-nutrient learning is a part of the learning theory based on Pavlovian conditioning in which flavors can act as sensory stimuli that can be coupled to the postingestive consequences elicited after consuming a certain food (Booth, Mather, & Fuller, 1982; Brunstrom, 2005).

A person's previous experience with eating a food to satiation is an important factor in establishing expected satiation. Irvine and colleagues compared expected satiation of wine gums (a chewy, pastille-type sweet candy) before and after eating wine gums to fullness in a laboratory setting. Wine gums were chosen because they are generally not eaten to satiation, or as a meal, so participant's previous experience with this food was limited. Results demonstrated that participants who had greater experience eating wine gums to a high level of self-reported fullness expected them to provide greater satiation compared to participants who had no previous exposure to these candies (Irvine et al., 2013). It is not known if these findings will generalize to other types of foods, but this implies that previous experience with a food, likely through flavor-nutrient learning, could be a critical component of determining the effect of portion size on energy intake.

Other studies in adults show positive relationships between food familiarity and expected satiation (Brunstrom et al., 2008; Wilkinson et al., 2012) but few studies have examined the effect of familiarity on expected satiation in children. In one study by Hardman and colleagues, 11- to 12-year-old children gave higher ratings of expected satiation to snack foods if they had greater previous experience with these foods. In addition, the relationship between familiarity and expected satiation was stronger for high-energy foods (Hardman et al., 2011)). These findings are in agreement with results from adults (Irvine et al., 2013) and indicate the importance of previous exposure to foods in order to learn the associated post-ingestive consequences of consumption (Hardman et al., 2011). Clarifying how expected satiation is established is important as it may influence individual differences in response to portion size manipulations.

Are large portions of food more rewarding?

The previous studies from Brunstrom and colleagues (Brunstrom et al., 2008; Hardman et al., 2011; Irvine et al., 2013; Wilkinson et al., 2012) suggest that prior experience with a food is a critical component to determining how much of that food one chooses to eat on any given occasion. But does this relationship apply to all foods equally (e.g. treat foods, special occasion foods, chocolate)? Additional insight into this question could be achieved by investigating how the rewarding properties of food interact with manipulations in portion size to influence energy intake. One key question is whether or not larger portions of food are more rewarding than smaller portions, independent of other food attributes like palatability. Survey data show that consumers are drawn to larger packages of food at the supermarket (Phillips, 1990; Shapiro, 1993) and report that larger portions are a key factor driving restaurant choices (Carangelo, 1995). These data suggest that at the very least, large portions are appealing to consumers and drive purchases. Studies that have examined whether large portions are also more rewarding are reviewed in this section.

In one study by Burger, Cornier, Ingebrigtsen, & Johnson (2011), adults were shown photographs of small and larger portions of foods that included fruits, sweet-fat snacks (e.g. cookies), savory-fat snacks (e.g. french fries), vegetables, and proteins (e.g. chicken, steak). Overall, participants rated large portions more appealing and reported a higher desire to eat them compared to small portions of the same foods. These effects were stronger in overweight individuals than they were in lean individuals. Interestingly, in this study, energy density of the foods was negatively correlated with ratings of appeal and desire to eat, a result that seems contrary to the fact that more energy dense foods often have higher palatability. These findings inform understanding of the mechanisms of the portion size effect because they suggest that the visual cue of portion size alone is associated with reward-related responses, despite the fact that participants were not consuming the foods. However, it is possible that these results would be different if participants were actually tasting or eating the foods, as opposed to looking at pictures.

One limitation of the study by Burger and colleagues (2011) was that it looked at ratings for single foods, but most foods are eaten as part of a meal. To explore the impact of food reward on meal-size selection, Brunstrom and Rogers (2009) had adults rate liking, utility, and expected satiation of food images. Food utility was measured by having participants report how much they would be willing to pay for a food, defined as a measure of food reward. In addition, participants reported the ideal portion size they would choose for a lunch. Results showed that ideal portion size was highly correlated to expected satiation, such that foods that were perceived to be more filling were selected in smaller portions. Contrary to their expectations, food utility was inversely related to energy-density and portion size. Foods that were perceived as more rewarding were selected in smaller, not larger portions. This was primarily explained by the fact that participants expected less energy dense foods to provide more satiation, so these foods were selected in smaller portions (Brunstrom & Rogers, 2009). These findings are supported by a related study from Brunstrom and Shakeshaft (2009), who found an inverse relationship between portion size and food reward. While this may seem counterintuitive, Brunstrom and Shakeshaft (2009) hypothesize that this is due to the fact that portion size selection is driven by expected satiation, and foods that are expected to deliver greater satiation are selected in smaller portions because of this. This research suggests a complex relationship between food reward and the portion size effect that is driven by how filling a food is perceived to be.

Some individuals may be more susceptible to the portion size response due to heightened or impaired sensitivity to reward (Davis & Fox, 2008). Current controversial evidence points to multiple theories of reward-system “flaws” that may lead individuals to excess consumption. One line of evidence supports that individuals may be at higher risk of overeating due to increased activation of the brain’s mesolimbic reward system in response to food, which leads to excess energy intake (Davis et al., 2007; Franken & Muris, 2005). The direct link between reward sensitivity and weight status remains unclear, though one study did find reward sensitivity to be positively associated with emotional overeating (Davis et al., 2007). An alternative notion is that some individuals may have a sluggish or under-responsive reward system, which is supported by studies demonstrating a reduced dopaminergic response in the striatum in response to food-related stimuli (Blum et al., 2000; Kenny, 2007). In this argument, excess consumption of highly palatable foods is hypothesized to be a response to an under-responsive reward system in order to help normalize brain dopamine levels (Stice, Yokum, Blum, & Bohon, 2010; Wang et al., 2001). Portion size seems to be closely related to reward, and this relationship may be partly driven by how filling a food is perceived to be. However, this relationship is likely influenced by individual differences in reward sensitivity and/or food cue responsiveness (Fisher et al., 2012) that may contribute to higher susceptibility to the portion size effect in some individuals.

Ongoing studies to determine the neural mechanisms of the portion size effect

To better understand how reward and other neural pathways impact portion size susceptibility, we present an overview and preliminary findings of a study from our laboratory that is applying neuroimaging to identify brain regions associated with the portion size effect. In this study, we are using functional magnetic resonance imaging (fMRI) to answer the following questions: (1) Do larger portions of foods activate distinct brain regions (e.g. reward regions, inhibitory regions)?; (2) Do brain responses to pictures of large portions of foods correlate with eating behavior under controlled laboratory conditions?; and (3) Are there individual child characteristics (e.g. weight status, reported loss of control eating) that predict neural activation patterns to portion size? Answering these questions will provide additional insight as to why some children overeat when presented with large portions.

What can fMRI tell us?

Functional magnetic resonance imaging (fMRI) is one of the most popular neuroimaging methods because it is a non-invasive yet highly precise tool that utilizes blood-oxygen-level-dependent (BOLD) acquisition to obtain images of cortical activity in real-time (for advanced review of fMRI see Amaro & Barker, 2006). The growing body of literature using fMRI to investigate the response to food-related stimuli has begun to clarify the brain–behavior relationship involved in overeating. Neuroimaging studies have investigated brain mechanisms comparing fed vs. fasted state (Goldstone et al., 2009; Holsen et al., 2006), lean vs. overweight (Bruce et al., 2010; Killgore et al., 2003; Rothemund et al., 2007; Stoeckel et al., 2008) and high vs. low energy food images (Killgore et al., 2003; Killgore & Yurgelun-Todd, 2005; Rothemund et al., 2007; Stoeckel et al., 2008) but mechanisms related to visual differences in food (i.e. portion size, unit size, packaging, color) have not been investigated. Additionally, there is a gap in fMRI studies that measure the brain’s response to food cues in pre-pubertal children. The majority of fMRI studies are completed in adolescents or adults, which are two populations that differ greatly in stages of development compared to children (Blakemore, Burnett, & Dahl, 2010; Brenhouse & Andersen, 2011). At present, little is known about the neural mechanisms underlying eating behavior and food intake decisions before adolescence.

Evidence from fMRI studies identified a pattern of results that may inform our understanding of mechanisms underlying eating behavior and the portion size effect. Findings reviewed to date show increased activation in brain areas related to reward and food-related memories, including the orbitofrontal cortex (OFC), in obese relative to lean children (Bruce et al., 2010; Killgore & Yurgelun-Todd, 2005). The OFC functions in food seeking-behavior (Alexander, Benson, & Stuss, 1989; Thorpe, Rolls, & Maddison, 1983; Volkow, 2002), suggesting that overweight children could have increased motivation to seek energy-dense foods. Differences in activity in additional brain regions of interest have been characterized as well, including the insula, nucleus accumbens (Bohon & Stice, 2011; Stoeckel et al., 2008) and limbic areas (Killgore et al., 2003), when obese vs. lean individuals view images of food. An important limitation to these studies is that the individuals are already overweight prior to neuroimaging testing; therefore the causal relationship between the brain's response to food and obesity cannot be determined. Understanding the neural processes involved with responding to differences in food portion size and understanding how these brain regions relate to obesity may inform the development of more effective obesity prevention programs. Several brain regions that are hypothesized to be involved in the portion size effect include reward regions (e.g. insula, nucleus accumbens, OFC), executive function and decision making (OFC, prefrontal cortex), visual and spatial processing (e.g. occipital lobe), and spatial processing (e.g. hippocampus and parietal cortex).

Challenges of conducting fMRI with children

When planning fMRI studies with children, there are several factors to consider that can impact image quality and study results. Children are less able to endure lying still for extended periods of time and may be more anxious in the fMRI environment due to loud noises and large machinery. Scan success rates have been estimated between 76% and 79% for typically developed children 6–9 years old with improvement to 96% for children 10 years and older (Byars et al., 2002; Yerys et al., 2009). In children, scan success can be influenced by several factors such as participant movement, scanner artifacts, and scan duration. In the present study, we made a highly conservative estimate of a 50% success rate, defined as completion of the anatomical reference scan and at least one functional run. Our preliminary scan success with 7- to 10-year-olds (n = 15) has been approximately 87.5%. An additional consideration is length of the scanning paradigm, which should be shortened to fit the limited attention span of a child. Our scanning paradigm is designed for completion in less than 30 minutes and allows short breaks between each functional run to ensure child comfort in proceeding with the remaining runs of the fMRI battery.

Designing neuroimaging paradigms to assess response to portion size

In addition to making accommodations to allow optimal testing of children, another key question involves the design of the fMRI paradigm. A limitation of using fMRI to understand the neural mechanisms underlying eating behavior is that participants cannot actually eat while in the scanner. Previous studies have shown pictures of food (Bruce et al., 2010; Cornier et al., 2013; Holsen et al., 2005, 2006; Killgore et al., 2003), food-related words or scripts (Hommer et al., 2013) or provided small samples of foods to taste (Small, Zatorre, Dagher, Evans, & Jones-Gotman, 2001) and results can vary depending on the method used. In addition, all of these methods lack translation to eating under free-living conditions. In order to make relevant connections between children's response to pictures of foods in the fMRI and their actual eating behavior, the present study includes four test-meal visits of both high and low energy-dense foods that are served for either lunch or dinner. The foods served at these test-meals are common, well-liked items that vary by energy density and portion size to correlate closely with the images children see in the magnet.

With respect to the design of the fMRI paradigm, there are several approaches one could take to isolate the neural response to food portion size. A naturalistic approach might involve showing pictures of actual "supersize" foods and/or meals and comparing them to the smallest size available (e.g. Subway® footlong vs. a 6-inch sub or Starbuck's ® Venti vs. a Tall/Small Coffee drink). In the present study, we decided against this approach due to potential confounding effects on the brain from food brand logos (Bruce et al., 2013, 2014). Instead, we opted for a more controlled approach. We selected 30 common high-energy dense foods (>1.5 kcal/gram) and 30 common low-energy dense foods (<1.5 kcal/gram) and photographed them at two levels of portion size (small vs. large) based

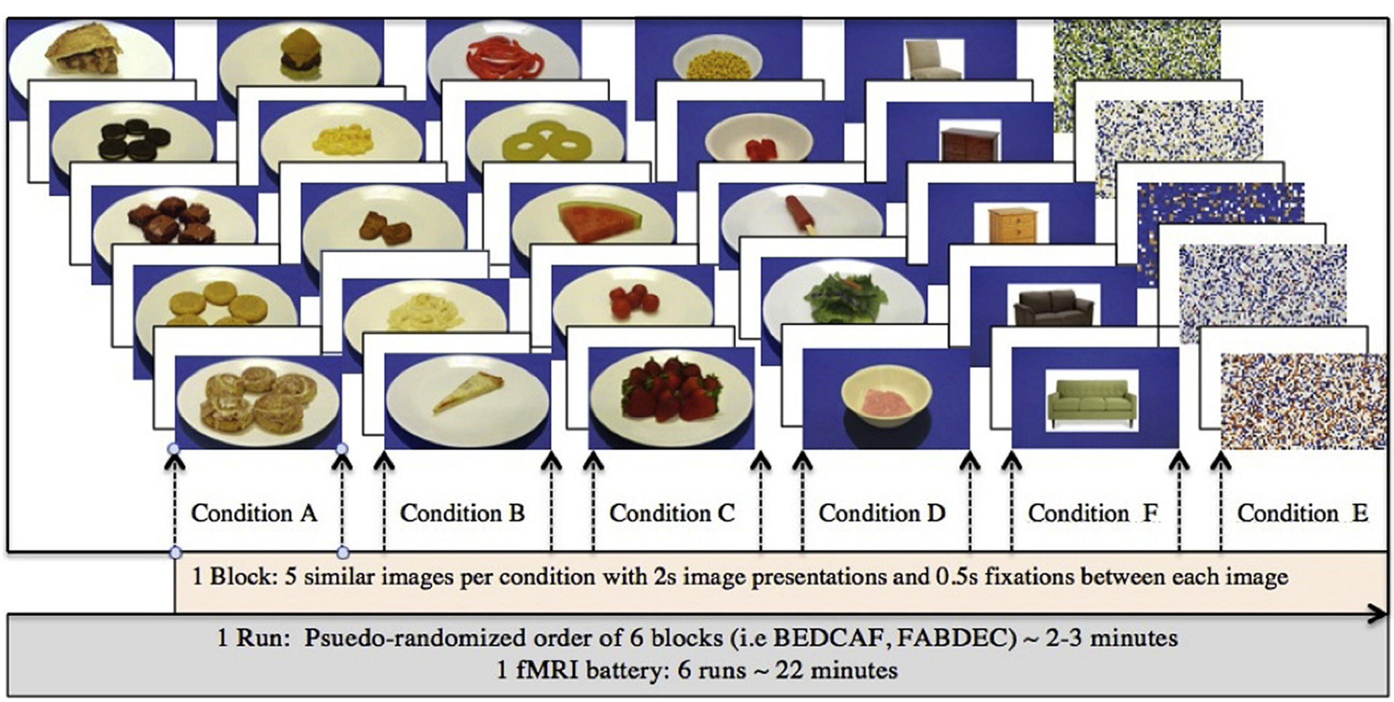

Fig. 2. The fMRI paradigm we are using is a block-design comparing children's BOLD fMRI response to 6 conditions (A = Large Portion/High Energy Density; B = Small Portion/High Energy Density; C = Large Portion/Low Energy Density; D = Small Portion/Low Energy Density; E = Control 1 (furniture); F = Control 2 (scrambled images). Images are shown to children for 2 seconds, with a 0.5 second fixation cross in between. Blocks are presented to children in a pseudo-randomized order to ensure that no more than two food conditions are shown before a control condition. The time between blocks is jittered (varied between blocks) and ranges from 2 to 20 seconds to avoid habituation to the images.

on data of consumption patterns for age appropriate children reported in the Continuing Survey of Food Intake of Americans – CSFI and CSFII (Smiciklas-Wright, Mitchell, Mickle, Goldman, & Cook, 2003). The small portion size was selected as the size of the food at the 10th % for children this age, while the large portion was at the 90th %. In this way, the images are realistic to what children might actually see or eat in their daily lives. The food photographs were taken by researchers using a high-resolution camera at a height and angle that reflect what a child might see if they were to view the plate from above when seated at a standard table. All foods were photographed on a standard white plate with blue linen background and were edited via GIMP image manipulation software to ensure consistency of color, size, and depth perception. For example, the M&M logo was removed from the candy using an image manipulation program (GIMP) to avoid issues of brand loyalty. In addition, two control, non-food conditions were created against which children's neural activation to portion size and energy density was compared. One non-food block was created using images of furniture items. A final control condition consisted of an equal number of scrambled images from the other 5 conditions (large portion/high energy density; small portion/high energy density; large portion/low energy density; small portion/low energy density; and furniture) to control for visual similarities (e.g. brightness, color) across the conditions. This block design allows us to contrast categories of interest highlighted in this review such as food vs. non-food, high-energy density vs. low-energy density, large portions vs. small portions and subsequent interactions to determine their relationship to neural reward and inhibitory pathways. Furthermore, this design allows for greater retention of data from functional runs in the event that a child cannot complete the entire fMRI battery of 6 functional runs after an anatomical scan (see Fig. 2).

Designing studies to assess the impact of individual differences

Not all children are equally susceptible to overeating when served larger portions (Fisher, 2007; Orlet Fisher et al., 2003). This indicates that there are environmental and/or biological factors that mediate this behavior. Identifying these factors could help inform the development of more effective interventions to prevent childhood obesity. However, little is known about why some children are more sensitive to the portion size effect than others.

One factor that could moderate the strength of the portion size effect is differences in eating behavior. Many questionnaires have been developed to measure and classify eating behavior. One example is reported loss of control (LOC) eating. Loss of control occurs within the context of an eating episode in which children or adults report a lack of control over their eating, independent of the actual amount of food consumed (Tanofsky-Kraff, Faden, Yanovski, Wilfley, & Yanovski, 2005; Tanofsky-Kraff, Marcus, Yanovski, & Yanovski, 2008; Tanofsky-Kraff et al., 2004, 2011). Children who report greater LOC eating are more susceptible to weight gain over time than non-LOC children (Tanofsky-Kraff et al., 2008), and they are less likely to consume regular meals and have increased snacking (Matheson et al., 2012). The LOC questionnaire is a pre-clinical measure of binge eating disorder that consists of twenty questions, the first of which screens whether during the last 3 months the child has ever felt that he/she was not able to stop eating, or control the type/amount of food they ate. If the child reports yes to LOC, the researcher proceeds to the remaining questions that ask more detailed information regarding the child's emotional state during perceived LOC (Tanofsky-Kraff et al., 2009). We predict that children who report previous episodes of LOC might be more responsive to the portion size effect than those who do not. Our

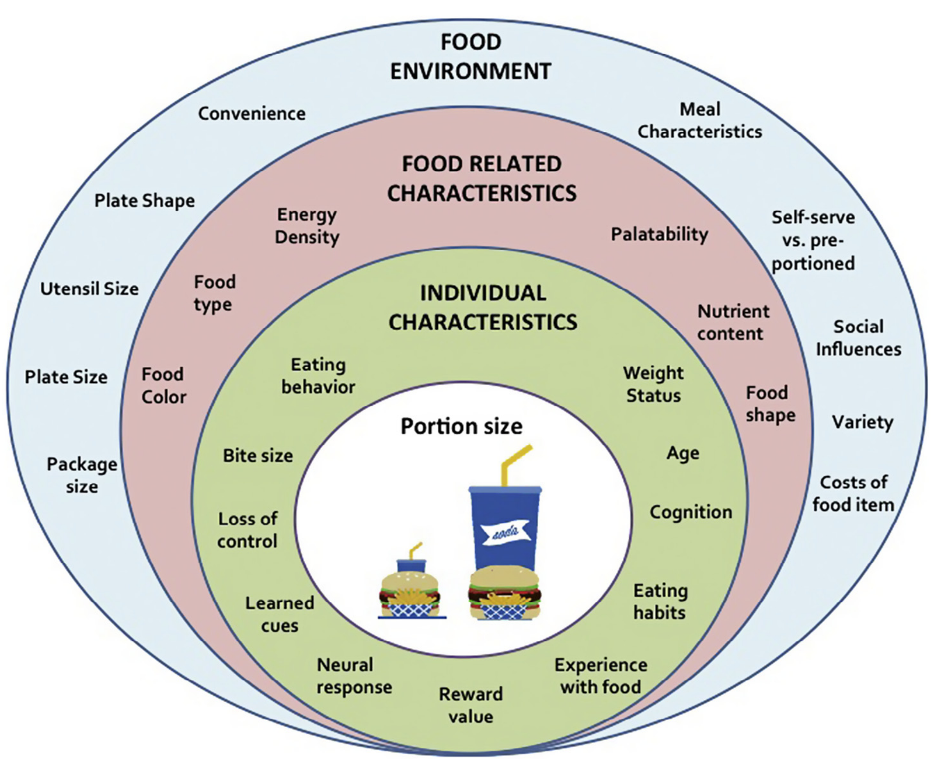

Fig. 3. Susceptibility to the portion size effect can be influenced by a number of characteristics. At the individual level, age, reward value of food, loss of control, bite size, learned response, and weight status. In addition, food-related characteristics, like palatability, energy density, food shape and color might also influence portion size susceptibility. Finally, the food environment influences portion size response. For example, plate size, utensil size, and package size were discussed in this review. Additional items that are potentially important include whether children are allowed to self-serve, social and peer influences, and perceived value or cost.

preliminary findings in children (n = 33) show that those who reported LOC consumed significantly more (153 kcal; $p < 0.05$) than non-reporters when served a test-meal that was 67% larger than the reference test-meal (English et al., 2014), even though change in rated fullness after the meal did not differ by reported LOC. These findings are preliminary, and a larger sample size is needed to confirm the results. Assessing individual differences in children's eating behaviors in response to portion size might help to identify modifiable factors that can be targeted by interventions (Fisher et al., 2012).

Discussion and implications for treatment

A clearer understanding of the mechanisms underlying the portion size effect is a critical step toward developing more effective and sustainable childhood obesity interventions. Several likely contributors to the portion size effect were reviewed in this paper. These and additional factors reviewed in Fig. 3 include food environment variables such as convenience, meal characteristics and social influences. In addition, food related characteristics like food type and nutrient content, as well the energy density and palatability, might also influence the strength of the portion size effect. Finally, individual differences across children in eating behaviors, perceived loss of control, age, and body weight might moderate the portion size effect. Future studies in larger, more representative samples are needed to better understand how these factors interact to influence portion size susceptibility.

Although more research is needed, several intervention strategies are implicated by the studies that have been reviewed. In children, using smaller plates was effective at reducing the amount of lunch children both self-served and consumed (DiSantis et al., 2013), although the effectiveness of this strategy over the long-term is unknown. In addition, expectations of the satiating potential are higher when foods are more familiar to children (Hardman et al., 2011), suggesting that interventions to increase children's exposure to lower energy-dense foods such as fruits and vegetables, might be an effective strategy to moderate energy intake (Ello-Martin, Ledikwe, & Rolls, 2005). One additional way to combat the portion size effect could be to decrease the energy density of foods that are served. Rolls and colleagues have found that individuals eat a consistent volume of food across eating occasions, so reducing the energy-density of foods results in lower energy intake (Leahy, Birch, Fisher, & Rolls, 2008). Neuroimaging studies of brain-eating behavior connections may be able to identify modifiable characteristics to target in interventions.

In summary, this review provides justification for understanding *why* and *how* portion size impacts energy intake before interventions are designed to target this behavior. We reviewed several possible mechanisms behind the portion size effect, including visual cues, anchoring and adjustment, learning, and reward. While somewhat speculative, clarification of these proposed mechanisms may be assisted through isolation of the neural response to food portion size. We recognize the potential for other confounding factors such as prior food experiences, food color, food shape, and social influences (variety, cost, convenience, etc.) that are beyond the scope of the current review but would be worthwhile for future investigations.

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