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Plenary Lecture

Sensory control of energy density at different life stages

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Taste preferences, food choices and eating habits all change with age. The transition from childhood to adolescence and adult life is associated with reduced sweet taste preferences, lower sugars consumption and reduced energy density of the diet. Ageing is associated with elevated acceptance of bitter tastes, elevated preferences for vegetables and salad greens, and increased consumption of whole grains, vegetables and fruit. The age-associated drop in energy intakes is achieved through a reduction in the weight and volume of food consumed, as well as a reduction in the overall energy density of the diet. Energy density drops from a peak of 5 kJ (1.2 kcal)/g in adolescence and early adult life to a low of 3.1 kJ (0.75 kcal)/g for adult women aged 45–54 years. Older adults, particularly women, consume less fat and saturated fat and more fibre and vitamin C, suggesting a shift in consumption from snacks, sweets and desserts towards grains, vegetables and fruit. These changes in food preferences and eating habits are associated, on a population level, with a decline in preferences for sweet taste and with increased acceptance of bitter tastes. At present there are no data to show a causal relationship between age-related changes in sensory function and the selection of a more bulky energy-dilute diet. However, it is a plausible hypothesis that sensory factors mediate adjustments in energy density of foods at different life stages.

Energy density: Palatability: Sugar and fat: Life cycle: Food preferences

Energy density of foods, as opposed to their macronutrient content, is said to be the major influence on energy intakes (Prentice & Poppitt, 1996; Seagle *et al.* 1997; Rolls & Bell, 1999). This argument is based on the premise that, under *ad libitum* conditions, people consume a constant weight or volume of food (Prentice & Poppitt, 1996; Seagle *et al.* 1997; Rolls & Bell, 1999). Daily energy intakes would then depend on food choices and on the energy density of the diet. Since bulky low-energy-dense foods provide less energy per unit volume, they should, in theory, lead to reduced energy intakes and therefore weight loss (Poppitt, 1995). Lowering the energy density of the diet has become a novel and highly-publicised approach to weight reduction (Drewnowski, 1998a).

Strictly speaking, this approach is not new. Energy-dilute foods have long been available in the food supply. Raw vegetables and fruit, salad greens, soups and beverages provide between 0.4 and 2.1 kJ (0.1 and 0.5 kcal)/g (Drewnowski, 1998a) However, consumer preferences

often run towards sweet and high-fat foods, including snacks, confectionery, sweets and other desserts (Drewnowski, 1993; Green *et al.* 1994). Generally, dry energy-dense foods contain sugar and fat, whereas energy-dilute foods contain water, dietary fibre and sometimes protein. Past and present dietary guidelines for health and weight control suggest replacing energy-dense foods with a wider range of grains, vegetables and fruit (Havas *et al.* 1994; Morreale & Schwartz, 1995).

However, bulky low-energy-dense foods tend to be less palatable than the more energy-dense foods. Arguably, foods are palatable because they deliver concentrated energy per unit volume. The overeating of foods high in sugar and fat has been ascribed to their palatability and low satiating power (Carroll, 1983). While the volume of food can be expanded by the addition of water, fibre or even air, the resulting food product is often less acceptable to the consumer. Although researchers claim that energy density and palatability are independent variables, any child knows

Abbreviation: NHANES, National Health and Nutrition Examination Survey.

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that energy-dilute spinach is less palatable than energy-dense chocolate. At a young age energy density equals palatability and vice versa.

However, energy requirements change with age; so do food preferences and food consumption patterns (Carroll, 1983; Rolls & Drewnowski, 1996). It may be that adults at different stages of the life cycle regulate energy intakes by altering the energy density of the diet, switching from energy-dense confectionery and sweets to more grains, vegetables and fruit. Taste preferences may mediate this shift in food choices, since sensory responses to sweet, fat and bitter also change as a function of age. The present hypothesis is that age-associated shifts in energy density of the diet are mediated, at least in part, by the sense of taste.

What is energy density?

Many investigators believe that energy-dense foods are those that contain fat or sugar, or both; a view which is only partly correct. In reality, the key influence on energy density is water, or the lack of it (Drewnowski, 1998a). Raw vegetables and fruits are naturally low in energy density because of their high water content. In soups, stews, juices and liquid-formula diets, water is the primary means of lowering energy density per unit volume. An analysis of 100 frequently-eaten foods in the US diet, adapted from the Health Habits and History Questionnaire (Block *et al.* 1985, 1986), showed that energy density was almost wholly determined by the proportions of water and fat. The food list included foods from the five major food groups (meats, dairy, grains, vegetables and fruit) as well as alcohol, sugar and cooking fats (selected examples are shown in Table 1).

Table 1. Energy density and water content of selected common foods

Food item	Energy density		Water content (g/kg)
	kJ/g	kcal/g	
Candy, milk chocolate	22.6	5.4	10
Cereal, granola type	19.5	4.7	50
Doughnut, cake type	17.8	4.3	200
Bread, white	10.9	2.6	370
Ice cream sundae	7.5	1.8	600
Potato, baked	4.6	1.1	710
Yogurt, fruit flavoured	4.4	1.1	850
Banana cream pudding	4.4	1.1	730
Yogurt, low-fat plain	2.6	0.6	850
Oranges, raw	2.0	0.5	870
Jell-O	2.6	0.6	850
Soda, cola type	1.7	0.4	890
Spinach, boiled	1.0	0.2	910
Tomato juice	0.7	0.2	940
Salad, green	0.7	0.2	960
Soda, diet type	0.0	0.0	1000

As shown in Fig. 1, foods with a lower energy density contained more water per unit weight. In contrast, energy-dense foods tended to be richer in fat (Fig. 2). Stepwise multiple regression showed that water content alone accounted for 85 % of the variance in energy density, while water and fat together accounted for 99 % of the variance. While the energy density of foods can range from 0 to 37 kJ/g (energy density of pure fat), the mean energy density of frequently-eaten foods in the US diet was of the order of 4–6 kJ/g.

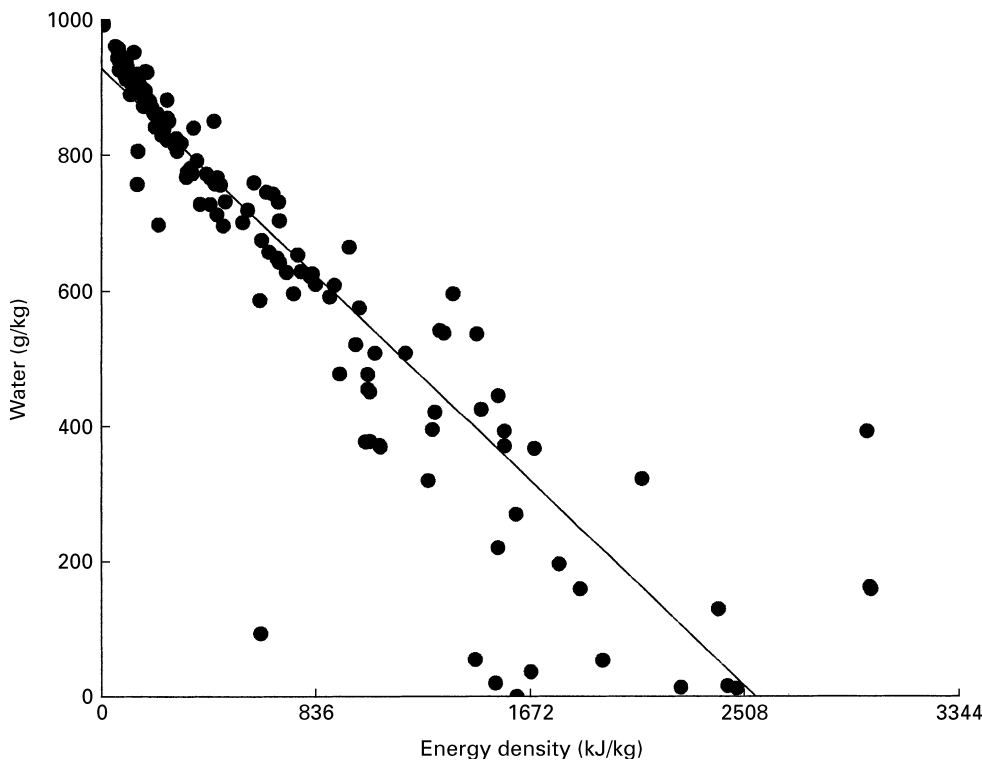


Fig. 1. The relationship between energy density (kJ/kg) and water content of foods (g/kg). (From Drewnowski, 1998a.)

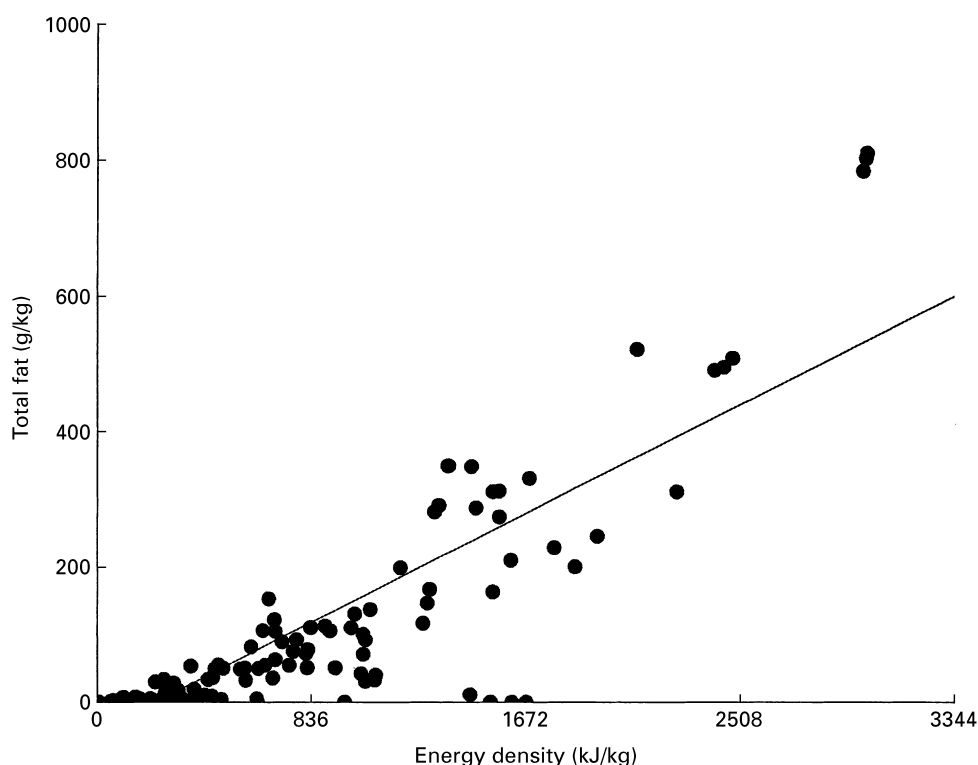


Fig. 2. The relationship between energy density (kJ/kg) and fat content of foods (g/kg). (From Drewnowski, 1998a.)

Energy density by life stages

National Health and Nutrition Examination Surveys (NHANES) are a major source of periodic information on the dietary, nutritional and health status of the US population (Carroll, 1983; McDowell *et al.* 1994). In addition to providing data on energy and macronutrient intakes, the NHANES II survey (1976–80) provided information on the amounts (g) of foods and beverages consumed daily (Carroll, 1983). These data were based on 24 h food recalls.

It is well established that daily energy intakes peak in adolescence or early adult life and then continue to decline with age (see Fig 3). Individuals consume less energy as they get older, whether by virtue of lower BMR or sharply reduced physical activity. It is less-well known that the volume of food consumed also declines with age, although perhaps to a lesser extent. Older adults in the NHANES II data set achieved their lower energy intakes by consuming a progressively lower volume of food. As shown in Fig 4, the mean daily weight (g) of foods and beverages consumed was sharply influenced by both sex and age (Carroll, 1983).

The amounts (g) of fat, carbohydrate and protein consumed per kg food also declined with age. As a result, the overall energy density of the diet dropped from a peak of 5 kJ/g in childhood and adolescence to a low of 3.1 kJ/g for adult women in the 45–54 years age-group. These data are summarized in Fig 5. Given that intakes of vitamin C (mg/4.2 MJ) among adults showed a sharp increase after the age of 35 years, particularly for women, it seems likely that the reduction in energy density was achieved through increased consumption of vegetables and fruit.

Food choices by life stages

Both food preferences and eating habits change with age. Studies on taste and ageing have noted an age-associated decline in taste function that was more pronounced for bitter than for sweet tastes (Rolls & Drewnowski, 1996). A corresponding decline in the sense of smell was associated with altered hedonic responses to food (Schiffman, 1993). Food preferences are known to shift during adolescence and early adult life away from sweet foods and towards a more diversified diet that includes fewer energy-dense foods and more vegetables and fruit (Drewnowski, 1989; Birch & Sullivan, 1991). A telephone survey study (Krebs-Smith *et al.* 1995), conducted before the 5-A-Day project (see Havas *et al.* 1994), found that reported liking for vegetables was age-dependent and was a significant predictor of vegetable intakes.

A re-analysis of classic studies on food preferences conducted in 1974 with young and largely male Army personnel showed that food preferences increased with increasing energy density of foods (Meiselman *et al.* 1974). However, that observation may hold only for children, adolescents and physically-active individuals in a state of energy need. As societies transit from under- to over-nutrition, selecting high-energy foods may no longer have a survival value. While active young men of two decades ago may have preferred steak and cake to yogurt and Brussels sprouts, many dieting women report precisely the opposite. Women, particularly older women, consistently report high preferences for energy-dilute vegetables and fruit (Drewnowski, 1997). The relationship between food preferences and energy density is most probably modulated

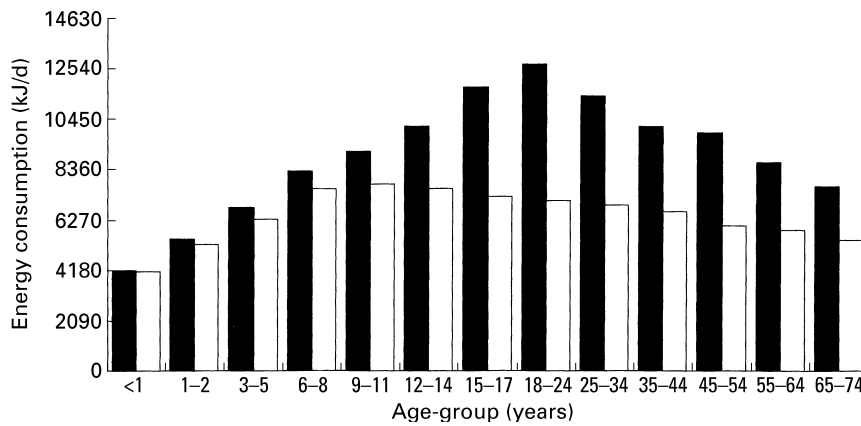


Fig. 3. Mean energy intakes (kJ/d) by age-group in the National Health and Nutrition Examination Survey II data (1976–80; Carroll, 1983). (□), Males; (■), females.

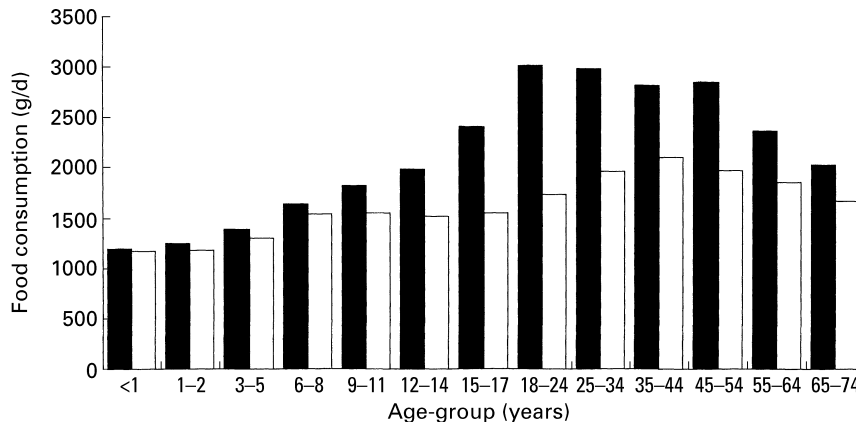


Fig. 4. Mean food consumption (g/d) by age-group in the National Health and Nutrition Examination Survey II data (1976–80; Carroll, 1983). (□), Males; (■), females.

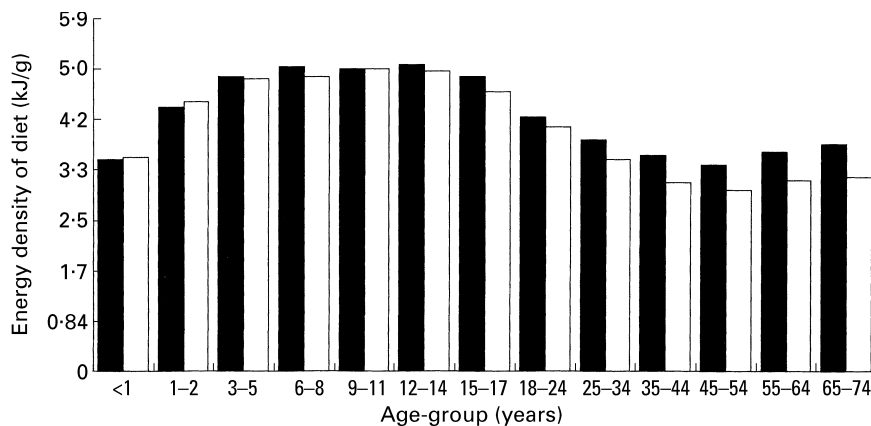


Fig. 5. Mean energy density of the diet (kJ/g) by age-group in the National Health and Nutrition Examination Survey II data (1976–80; Carroll, 1983). (□), Males; (■), females.

not only by energy needs, but also by the consumers' diet-related attitudes and behaviours.

However, the effects of age are dominant. In a clinical sample of female breast-care patients, age was the best predictor of dietary choices. Ageing was associated with growing acceptance of vegetables and fruit, and with reduced acceptance of some energy-dense foods. Women in

the top tertile by age (mean age 62 years) reported higher preferences for grains, vegetables and fruit than did women in the bottom age tertile (mean age 37 years). Older women also had reduced acceptance ratings for sweet beverages and for sweet high-fat desserts. These data are consistent with the results of some previous studies on food preferences of healthy adults. One correlational study (Logue & Smith,

1986) reported that preferences for sweetened soft drinks declined with age, whereas preferences for meat and dairy products remained unchanged. In a study of psychosocial influences on fruit and vegetable consumption (Krebs-Smith *et al.* 1995), older adults liked the taste of vegetables more than did younger adults.

Food intakes by life stages

Age was also a major predictor of food consumption patterns. Analyses of NHANES II data generally show that ageing was associated with lower energy intakes, lower intakes of fat and saturated fat, and higher intakes of dietary fibre, vegetables and fruit (Patterson & Block, 1988). In other studies by Block *et al.* (1985), also based on the NHANES II data set, older adults consumed more whole grains, vegetables, more cruciferous vegetables, green leafy and other vegetables, and more fruit than did younger adults (Carroll, 1983; Patterson & Block, 1988). Adults over the age of 59 years were more likely to consume fruit, tomatoes, breakfast cereals and whole-grain breads than the 18–59 years age-group, and less likely to consume sweets, snacks and carbonated sugar-based beverages (Cronin *et al.* 1982). Consumption of at least five servings of fruit and vegetables daily, as outlined by the 5-A-Day Program (Havas *et al.* 1994) increased as a function of age. Data obtained from 23 699 adults in sixteen US states, as part of the Behavioral Risk Factor Surveillance System (Serdula *et al.* 1995), showed that twice as many women over the age of 65 years (29 %) complied with the 5-A-Day diet as opposed to women aged 18–24 years (14 %). According to DDB Needham Lifestyle Survey of 4000 consumers, the group that was most likely to consume five servings of fruit and vegetables daily were retired elderly women in poor health (Drewnowski *et al.* 1999).

Age and taste responsiveness

Children's food preferences and dietary choices are driven primarily by taste (Dobbing, 1987; Drewnowski, 1989). While adults tend to be more concerned with the nutritional and health qualities of the diet (Kristal *et al.* 1990), children react largely to sensory qualities of food (Drewnowski, 1989). Relative to adults, children show an exaggerated avoidance response to bitter tastes and an elevated liking of intensely-sweet foods (Drewnowski, 1989). Both responses play an important physiological role. The sense of taste serves to orient the child away from bitter poisons and towards nutritive foods that provide maximum amounts of energy per unit volume.

The innate pleasure response to sweet taste, observable at birth, provides a motivation for continued feeding (Blass, 1987). Generally, the more intense the sweet taste, the greater the pleasure response, particularly in infants and young children (Blass, 1987). Preferences for sweet taste and sugar consumption drop sharply between childhood and adolescence (Drewnowski, 1989). The decline, observed around puberty at age 12–14 years is more marked for girls than for boys. Boys continue to prefer more-intensely-sweet stimuli into late adolescence. Sugar consumption then declines in adult life.

Energy requirements of growing children and active adults need to be satisfied with high-energy-dense foods. The high energy density of fat (37 kJ/g) is itself a source of food reward. Fat is perceived largely through a variety of food textures from smooth and creamy to juicy, crunchy and tender. Fat serves to introduce new flavours into the diet, and children easily learn to like novel flavours provided they are associated with a concentrated source of energy, such as fat. Children's preferences for energy-dense chocolate (24 kJ/g) over energy-dilute spinach (0.4 kJ/g) are a necessary consequence of these natural physiological mechanisms. The sense of taste steers children towards energy-dense foods and so assures growth and survival.

The sensory appeal of energy-dilute foods is aided by sweetness. In general, sweet fruit are preferred over energy-dilute foods that are not sweet. Sweetened yogurt is preferred over plain yogurt, and sweetened soft drinks are preferred over plain or mineral water, especially by young people. The main reason is that the presence of sweetness also signals the presence of energy, a major physiological reinforcement to the hungry organism (Cabanac, 1971; Drewnowski, 1998b).

Energy density and palatability are therefore linked. In general, foods are palatable because their energy density is high (Drewnowski, 1998b). Sensory enjoyment of sugars and fats is directly related to the fact that they both represent concentrated and readily-available sources of energy. Sweetness and the oral sensation of fat are desirable attributes that are linked to palatability and enjoyment. Given a choice, young children prefer energy-dense foods to those that deliver less energy per unit weight (Johnson *et al.* 1991; Birch, 1992). So while energy-dense foods are palatable, they are not particularly satiating and tend to be overeaten. In contrast, energy-dilute foods deliver less energy per eating bout and are by definition more satiating, although generally less palatable. The interrelationships between energy density, palatability and satiety are shown in Table 2.

Once development and growth are completed, taste preferences and food-related attitudes undergo a profound change. Adults dislike intensely-sweet foods and show a much higher tolerance for bitter taste. While adults often seek out coffee, beer, alcohol, green and cruciferous vegetables and bitter citrus fruit, these foods are of no interest to young children. Health-related attitudes and behaviours play an increasingly important role in adult life, steering adults towards a more healthy diet. Most important, the reduction in energy intakes as a function of age may be

Table 2. A comparison of foods with low and high energy density (from Drewnowski, 1998a)

	High energy density	Low energy density
Weight or volume per portion	Low	High
Water content	Low	High
Fat content	High	Low
Key components	Fat, sugar	Protein, starch, fibre
Example	Chocolate	Spinach, porridge
Satiating power	Low	High
Palatability	High	Low

accomplished by a gradual adoption of low-energy-dense diets.

Age-associated changes in taste sensitivity may provide a partial explanation for the observed shift of some food preferences with age. Bitter taste acuity, including sensitivity to 6-*N*-propylthiouracil solutions, is known to decline with age (Weiffenbach, 1984), possibly favouring the consumption of bitter-tasting vegetables and salad greens (Subar *et al.* 1995). A better understanding of how sensory factors influence food preferences and the energy density of the diet may aid in the design of better dietary strategies for weight control.

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