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Analysis of energy density of food in relation to energy intake regulation in human subjects

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The relationship between energy density (ED) of food and drink consumption *ad libitum* and energy intake (EI) was analysed. EI was taken as average daily EI over the long term, and as EI during a single meal. Moreover, the distribution of EI over three ED categories was analysed. Average daily EI was related to ED of the food and drinks when ED was strongly influenced by specific macronutrients. When ED was strongly influenced by the weight of water, it was not related to EI. During a meal subjects monitored mainly weight, and to a lesser extent, the energy content of the food ingested. Therefore, covertly manipulated ED of a meal affected EI directly. The impact of ED on EI was modulated by dietary behaviours such as restraint. Overt manipulation of ED for 6 months showed that EI was adjusted to a decreased but not to an increased ED in dietary-unrestrained subjects, and that EI was adjusted to an increased but not to a decreased ED in dietary-restrained subjects. Knowledge of ED was shown to lead to an inverse relationship between portion sizes and ED during a meal. Average daily EI consisted of a distribution of EI over the three different categories of ED, so that obese women ate more of foods with a high ED and less of foods with a low ED compared with normal weight women (and nutritional guidelines). In conclusion, ED affected daily EI by means of macronutrient specific effects. EI from a meal with an unknown ED can become inversely related to EI through learning or conditioning. Therefore, the effect of ED on EI during a single meal observation cannot be extrapolated directly to the 24 h effect on EI. With regard to the treatment of obesity, a conscious decreased consumption of foods high in ED and an increase in consumption of low-ED food is necessary to decrease and subsequently maintain body weight, particularly in subjects with a sedentary lifestyle.

Macronutrient composition: Dietary restraint: Obesity: Energy density: Energy intake regulation

Energy intake and energy balance

Normally, human subjects are on average in energy balance over a week (Edholm & Fletcher, 1955). Man is a continuous nutrient metaboliser, but ingests food discontinuously. Therefore, tuning of energy intake (EI) to energy expenditure in order to maintain energy balance is required. This is achieved by an interaction of a variety of sensoric, gastrointestinal and metabolic factors that control the actual food intake pattern, i.e. meal size and meal frequency (Melanson *et al.* 1999*a*,*b*; Stubbs *et al.* 1999). In the short term, EI oscillates in the maintenance of energy balance.

Metabolisable energy and macronutrient composition

EI is not related in a straightforward fashion to the weight of food intake. Man derives his energy from the macronutrients carbohydrates, lipids, proteins and alcohol. The energy is released during the breakage of chemical bonds, and can be used for energy metabolism or can be converted or stored. Metabolisable energy is the gross energy minus energy in faeces and urine. Knowing the macronutrient composition of foods from chemical analysis, the metabolisable energy can be calculated by multiplying the weight of each nutrient by its metabolisable energy value, the Atwater factors. These are, for carbohydrate, protein, fat and alcohol, 16, 16, 37 and 29 kJ/g respectively. The relevant food characteristics that play a role in regulation of EI are: energy content, macronutrient composition, weight, and energy density (ED) (Melanson *et al.* 1999*a*; Stubbs *et al.* 1999). Moreover, sensory characteristics of food (taste, texture,

Abbreviations: ED, energy density; EI, energy intake; WW, weight of water.

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palatability) and variation in these characteristics also influence food intake (Drewnowski *et al.* 1992).

Energy density

Lately, attention has been paid to the role of ED in the regulation of EI (Westerterp-Plantenga *et al.* 1990*a*, 1996*a*,*b*; Stubbs *et al.* 1995, 1998*a*,*b*; Poppit & Prentice, 1996; Rolls & Bell, 1999; Westerterp-Plantenga, 2000*a*). ED is the total metabolisable energy from the different macronutrients, divided by the total weight of food and water consumption. This weight consists of the dry weight of these macronutrients (including the undigestible parts, e.g. non-digestible protein, resistant starch, fibre) plus the total weight of water (WW) consumed in and with the food.

Relevant questions

With regard to the role of ED in EI regulation, the relevant questions are:

(1) is daily energy intake related to the ED of food and drinks, and if so, which factors that determine ED contribute to this effect?
(2) is ED, energy content, or weight of food monitored subconsciously during food consumption?
(3) is food choice and portion size adjusted in response to ED?

Plan of the remaining part of this paper

(1) To gain insight into the effect of ED of food and drinks on average daily EI, three data sets from our laboratory were analysed (Goris & Westerterp, 2000; Westerterp-Plantenga, 2000*b*). The possible relationship between EI and ED was assessed. Then, the factors that determine ED and the factors that determine EI were analysed. The significance of the determinants of ED for the relationship between EI and ED was determined;
(2) the role of ED in determining the amount of food intake during a single meal was discussed;
(3) the relationship between ED, portion size and food choice was analysed.

The significance of the determinants of energy density for the relationship between energy intake and energy density

In the three data sets which were analysed (1), food availability was *ad libitum* with regard to choice, amount and frequency. The first data set was obtained from a study in which sixteen dietitians (age 34 (SD 9, BMI 22·1 (SD 2·3 kg/m^2) monitored their food intake for 1 week, using weighed food records. Their recording of EI was accurate, according to a method for the determination of water turnover using ^{2}H elimination, together with determination of body weight (Goris & Westerterp, 2000). The protocol was executed twice, with feedback after the first time (during which they lost weight by under-eating). For the present analysis the food records produced the second time are used, during which no under-eating or under-recording occurred (Goris & Westerterp, 2000). The second data set was from a study with female students (age 23 (SD 4), BMI 22·2 (SD 3·2) kg/m^2) in a respiration chamber. The days on which they ate *ad libitum*, which were always preceded by a day during which they were fed in energy balance so that they did not have to compensate for the previous day, are used for the present analysis (Westerterp-Plantenga, 2000*b*). The third data set is similar to the second, but for male students (age 25 (SD 6), BMI 22·9 (SD 3·1) kg/m^2) (Westerterp-Plantenga, 2000*b*).

Simple regression analysis was used. First, EI was analysed as a function of ED. Separately, EI was analysed as a function of the metabolisable energy provided by the macronutrients, and the gross weight of the macronutrients and WW. Third, ED was analysed as a function of the metabolisable energy provided by the macronutrients, and the gross weight of the macronutrients and WW.

Calculation of energy intake and energy density

As indicated earlier, ED is the total metabolisable energy consumed with the different macronutrients, divided by the dry weight of these macronutrients, which includes the undigestible parts, i.e. non-digestible protein (N), resistant starch, and fibre, plus the total WW consumed. This can be written as:

$$\mathrm{ED} = \frac{\text{carbohydrate (kJ)}+\text{protein (kJ)}+\text{fat (kJ)}+\text{alcohol (kJ)}}{\text{(carbohydrate (g)}+\text{protein (g)}+\text{fat (g)}+\text{alcohol (g)}+\text{water (g)}}.$$

The computer program that was used for food intake analysis calculates metabolisable energy and gross weight, including fibre, non-digestible protein, resistant starch, etc. (Voorlichtings bureau voor de Voeding, 1992).

The determinants of energy density and the relationship between energy intake and energy density

The relative quantitative contributions of the determinants of ED and of EI in the three data sets were analysed, using a simple regression analysis. Table 1 shows EI (kJ), energy (kJ) from carbohydrate, protein and fat, as well as the weight (g) of carbohydrate, protein, fat and water. It also shows ED, % solids from total weight of food and macronutrient composition (% energy) of the three data sets that were analysed. Table 2 gives the simple regression analysis for each of these three data sets, which shows the extent of linear correlation between the variables energy (kJ) from carbohydrate, fat and protein, and the weight (g) of carbohydrate, fat, protein and water *v*. ED, EI and % solids respectively of the total weight of consumption.

The relationship EI:ED was as follows: data set 1 (dietitians) r 0·38, $P = 0{\cdot}0001$; data set 2 (women) r 0·93, $P = 0{\cdot}0001$; data set 3 (men) r 0·17; $P = 0{\cdot}27$. From the regression analyses it appears that EI was related to ED (data set 2), when the relationship of ED to the energy content and weight of the macronutrients was similar to the relationship of EI to these macronutrients. In data set 2 both ED and EI were related to the energy content and weight of

Table 1. Energy intake and macronutrient composition from three data sets*

	Data set 1		Data set 2		Data set 3	
	Dietitians (*n* 16)		Females in respiration chamber (*n* 8)		Males in respiration chamber (*n* 8)	
	Mean	SD	Mean	SD	Mean	SD
EI (MJ)	9·4	2·3	9·7	1·0	14·5	3·4
C (MJ)	4·6	1·2	5·4	0·6	7·0	1·8
P (MJ)	1·3	0·3	1·4	0·1	2·2	0·5
F (MJ)	2·9	0·9	2·9	0·4	5·3	1·2
C (g)	288	77	338	36	438	115
P (g)	81	17	88	7	138	31
F (g)	78	25	78	11	143	32
W (g)	2665	934	2903	97	2735	1478
ED (kJ/g)	3·2	0·8	2·8	0·3	4·7	1·7
% Solid	14	4	15	2	25	9
C:P:F: (% energy)	49:14:31†		56:14:30		48:15:37	

EI, energy intake; C, carbohydrate; P, protein; F, fat; W, water, ED, energy density.
* Data set 1, Goris & Westerterp (2000); data sets 2 and 3, Westerterp-Plantenga, (2000*b*).
† 6 % energy from alcohol.

the macronutrients but they were not related to WW. Furthermore, there was also a relationship between EI and ED (data set 1), when ED and EI were both related to the energy content and weight of the macronutrients, but ED was negatively related to WW whereas EI was positively related to WW. There was no relationship between EI and ED when their relationships with the different components were quite different (data set 3). Here, EI was mainly related to the energy content and weight of macronutrients, and also, positively to WW. ED was only negatively related to WW.

Similarly to ED, % solids from total weight of food was related to EI (data set 1 and 2), when % solids of total weight of food was related to the macronutrients, but not when it was only related to WW.

Table 2. The extent of linear correlation between energy intake, energy density, % solid of the total weight, and energy content and weight of the macronutrients, in three different data sets

Data set†		*r*		
		EI	ED	% Solids
1 (Dietitians, *n* 16)	C (kJ)	0·81***	0·28**	0·33***
	P (kJ)	0·62***	0·16	0·15
	F (kJ)	0·81***	0·47***	0·35***
	C (g)	0·81***	−0·28**	0·33***
	P (g)	0·62***	−0·16	0·15
	F (g)	0·81***	−0·47***	0·35***
	W (g)	0·33***	−0·64***	−0·65***
2 (Females, *n* 8)	C (kJ)	0·54*	0·50	0·35
	P (kJ)	0·46	0·41	0·27
	F (kJ)	0·77***	0·85***	0·72**
	C (g)	0·54*	−0·50	0·35
	P (g)	0·46	−0·41	0·27
	F (g)	0·77***	−0·85***	0·72**
	W (g)	0·21	−0·15	−0·04
3 (Males, *n* 8)	C (kJ)	0·89***	0·23	0·22
	P (kJ)	0·98***	0·22	0·19
	F (kJ)	0·97***	0·27	0·26
	C (g)	0·89***	−0·23	0·22
	P (g)	0·98***	−0·22	0·19
	F (g)	0·97***	−0·27	0·26
	W (g)	0·66***	−0·77***	−0·76***

EI, energy intake; ED, energy density; C, carbohydrate; P, protein; F, fat; W, water.
*$P < 0·05$, **$P < 0·01$, ***$P < 0·001$.
† Data set 1, Goris & Westerterp (2000); data sets 2 and 3, Westerterp-Plantenga (2000*b*).

From the simple regression analyses it appears that ED can be predicted significantly by the weight (g) of fat, carbohydrate and water and by the energy (kJ) from fat and carbohydrate (Table 2). The variation in the relative proportion of protein was small, so it does not contribute much to the variation in ED.

ED represents energy (kJ)/weight, since the Atwater factors are defined in this way. ED does not represent energy (kJ)/volume. If volume is used, then one has to take the specific weight of the food into account, since weight = volume × specific gravity. Specific gravity of a food recipe changes, for instance, when air is added, as, for example, in a soufflé. This might have a very short-term effect, but it is by definition not an ED effect. Sometimes both weight and volume are used (Rolls & Bell, 1999), which might slightly confuse the interpretation of ED.

Explanations of the possible relationships between energy intake and energy density

The analysis on the three different data sets shows three different outcomes. The difference between the outcomes of data sets 1 and 2 is determined by the difference in variation in WW of total consumption. In data set 1 there was a variation in the WW consumed, which affected ED negatively and which was positively related to EI. In data set 2 the variation in the WW was too small to contribute to ED and EI. Both data sets show contributions of variations in macronutrients to ED and to EI; in both data sets EI was positively related to ED.

The difference between data set 1 and 3 is determined by the difference in the variation in macronutrient intake. Data set 1 shows a variation in macronutrients (carbohydrate and fat), which affected ED and which was positively related to EI. In data set 3 there was too little variation in macronutrient intake to contribute to ED. Both data sets 1 and 3 show the positive relationship between WW and EI, and the negative relationship between WW and ED. Data set 1 implies a relationship between EI and ED; data set 3 lacks this type of relationship. Data sets 2 and 3 show the largest differences. In data set 2 the relationship between EI and ED is determined by the weight and energy content of fat, and WW does not have any significance for this relationship. In data set 3 a relationship between EI and ED is absent, because of the dominant effect of WW on ED, the lack of effect of the macronutrients on ED, and the dominant effect of the macronutrients on EI.

From the differences between these three outcomes it was concluded that ED was related to EI, when ED was related to the energy content and the weight of macronutrients (data sets 1 and 2), and possibly but not necessarily to WW (data set 1). When water was the dominant component (WW) of ED, EI was not related to ED (data set 3). In other words, when the variation in ED was only determined by WW, ED did not play a role in EI regulation. This means that EI became independent of ED, when only the range in the WW determined the range of ED.

When EI was also determined by WW, WW correlated positively with EI, whereas it correlated negatively with ED. This concerns WW in the food, which is inclusive in food intake. It means that the EI from the food cannot take place without the accompanying water.

The analysis of the effect of % solids of total weight of food shows similar results to that of ED. It is important to discriminate between % solids and liquid, in a way that % solids only includes the dry weight of the foods and % liquid only includes the water in- and outside the foods. Otherwise the discrimination becomes arbitrary, e.g. a soup with a high total dry weight would be categorised as liquid, whereas a cucumber with a high WW would be categorised as solid.

The relationship between ED and EI is strong when the separate relationships of ED and EI to the macronutrients are similar. All macronutrients explained the variation in EI, with the weight of fat contributing most to EI, and also to ED. As soon as the effect of WW on ED became relatively large, the positive relationship between ED and EI became weaker, and disappeared.

Therefore, we cannot simply substitute the effects of the different macronutrients on EI regulation by the effect of ED (macronutrients and possibly WW, or mainly WW), as it is sometimes suggested (Rolls & Bell, 1999). Such a suggestion is based upon studies in which macronutrient compositions remained the same, but the dilution in the foods varied. From the dilution range of the same type of food the EI was higher from the less diluted food and lower from the more diluted food (Rolls & Bell, 1999). Since the relative contributions of the macronutrients were kept constant, the only effect on ED must have been WW. When we showed a large effect of WW on ED, such as in our data set 3, the relationship between EI and ED was absent, and it was the energy content and weight of the macronutrients that determined EI, irrespective of WW. In our data sets only WW was related to EI positively, which must have been the water in the food, as is discussed earlier. If the relationship between EI and ED is absent, it means that EI can consist of foods of any ED. From the observation that EI is greater when the food is less diluted and lower when the food is more diluted (Rolls & Bell, 1999), we cannot conclude whether this implies a significant relationship between EI and ED since the regression analysis is not known.

Specific effects of the determinants of energy density on energy intake

Water. With regard to WW, there is evidence on the possible role of water intake in satiety from a study by Himaya & Louis Sylvestre (1998). When the water is part of the food, it affects stomach emptying, and thus it affects satiety. When water is outside the food, it empties from the stomach straightaway, and does not affect stomach emptying of the other food, therefore it does not affect satiety. The rate of gastric emptying is largely controlled by the energy content of the stomach (Brouns *et al.* 1987) and the stretch receptors in the stomach signal energy content to the brain (Rayner, 1992). Thus, when water is part of the food it may contribute positively to satiety.

Fat. With regard to the weight of fat, many studies include examples of a change in % energy from fat, changing ED and subsequently affecting EI, e.g. Lissner *et al.* (1987), Kendall *et al.* (1991), Blundell *et al.* (1993), Green *et al.* (1994), Hulshof *et al.* (1995), Rolls (1995), Stubbs *et al.* (1995, 1996, 1998*a*,*b*), Cotton *et al.* (1996), Poppit & Prentice (1996), Westerterp-Plantenga et al. (1997*a*,*b*, 1998, 1999), Hill *et al.* (1998), Kelly *et al.* (1998).

The possible implication that fat replacement including reduction of energy content may have for the treatment of obesity, or for contribution to weight maintenance, appears not to be straightforward. A number of studies show different responses due to different subject characteristics, e.g. dietary restraint. In a 6 month reduced-fat *v.* full-fat study in dietary-restrained and -unrestrained men and women, we found that a reduced-fat diet in combination with unrestrained eating behaviour (which resulted in EI compensation), contributed to weight maintenance. Weight reduction was the consequence of a reduced-fat diet in combination with restrained, non-compensatory eating behaviour. A full-fat diet combined with unrestrained eating behaviour led to increased EI, although the gain in body weight did not reach statistical significance ($P = 0{\cdot}07$). Restrained eating behaviour with a full-fat diet prevented an increase in EI and body weight. Thus, the dietary-restrained subjects compensated with their EI for the increase in ED, whereas the dietary-unrestrained subjects compensated with their EI for the decrease in ED (Fig. 1; Westerterp-Plantenga *et al.* 1998).

In a study with covert fat replacement (23 g) by sucrose polyester during breakfast and lunch on two sequential weekdays, in dietary-restrained and -unrestrained women, we showed an EI reduction of 0·7 MJ/d ($P < 0{\cdot}05$) in the normal weight dietary-restrained women, but not in the dietary-unrestrained. In the dietary-unrestrained, EI reduction was 0·5 MJ/d (NS). These EI reductions resulted in 22 % EI compensation for the EI prevented by fat replacement in the dietary-restrained subjects, and in 44 % EI compensation in the subjects who lacked dietary restraint. The two sequential weekdays were part of 1 week when complete food intake was assessed; the two sequential

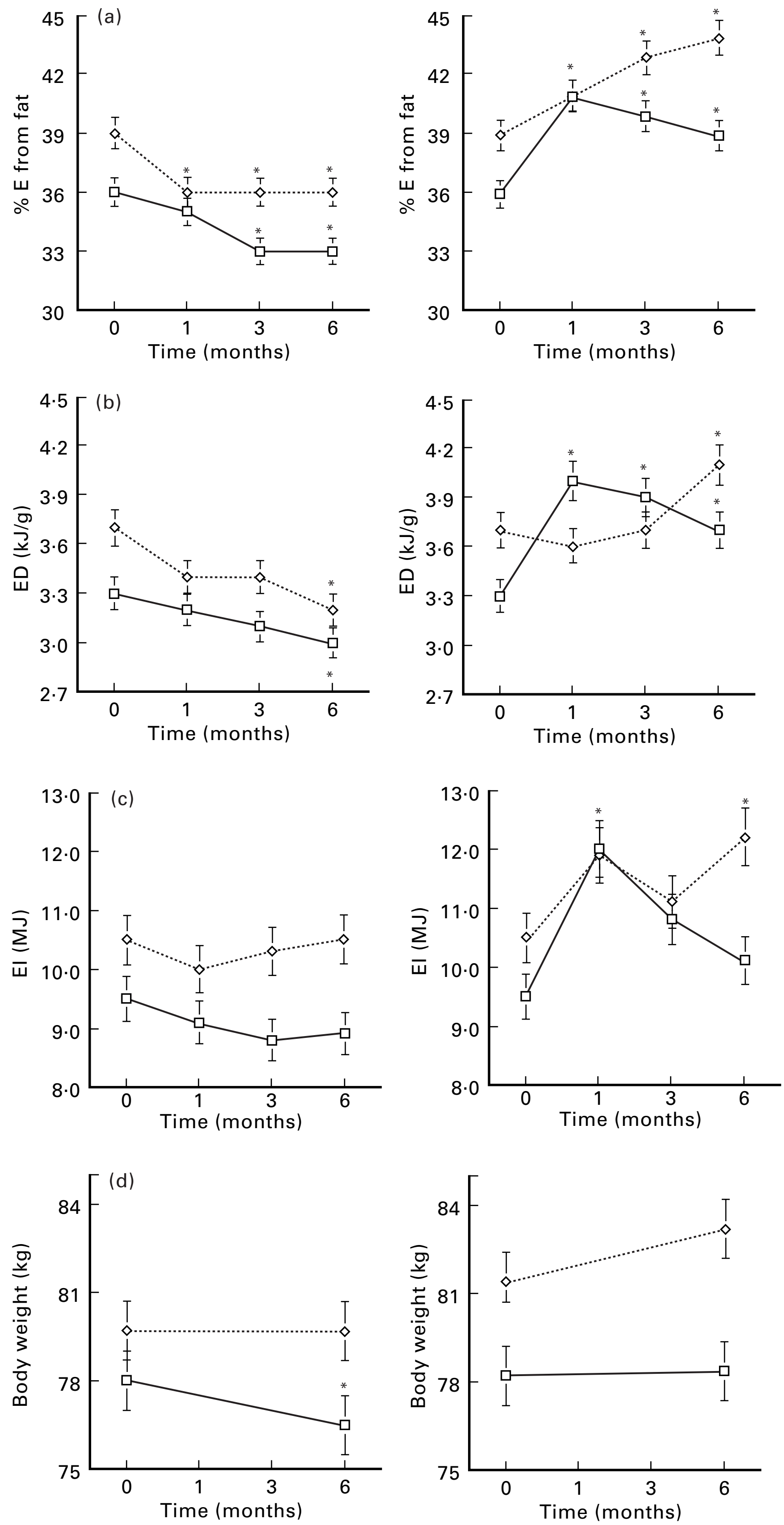

Fig. 1. (a) Percentage energy (%E) from fat, (b) energy density (ED) of total consumption, (c) average daily energy intake (EI) and (d) body weight in a 6 month trial in which dietary-restrained and -unrestrained men and women were maintained on a reduced-fat (left hand panels) or full-fat (right hand panels) diet (Westerterp-Plantenga *et al.* 1998). □, Dietary-restrained subjects; ◇, dietary-unrestrained subjects. Values are means with standard deviations shown by vertical bars. Mean values were significantly different from those at baseline: *$P < 0{\cdot}05$.

placebo days were part of another week with assessment of complete food intake. During another 2 weeks, subjects received a fresh box with labelled snacks every day. In 1 of these 2 weeks, all snacks in the boxes were full-fat snacks, and in the other of the 2 weeks, all snacks were present in both a full-fat and in a reduced-fat including reduced-energy form. When fat replacement was overtly present in snacks, the dietary-unrestrained and the post-obese dietary-restrained women showed an EI reduction of 0·6–0·7 MJ/d ($P < 0·05$), but the dietary-restrained women showed a non-significant EI reduction of 0·4–0·5 MJ/d (Westerterp-Plantenga *et al.* 1997*a*). In comparison, Hulshof *et al.* (1995) found, in a 12 d study with sucrose polyester as a fat replacer, no differences in any aspect of appetite in women, probably because the EI from the meals using the fat replacer was at the subjects' normal level, whereas the EI from the meals using fat was above their normal level. These results suggested short-term beneficial effects of fat replacement including reduction of ED, on EI and fat intake.

Carbohydrate. With regard to the role of carbohydrate in relation to ED, simple carbohydrates have received attention with regard to effects of their replacement by sweeteners, in order to lower ED, and subsequently EI. In this respect Drewnowski (1999) considers that the theoretical reduced EI with low ED foods, leading to body weight loss is arguable. There is also the question as to whether energy-dilute foods are as palatable as the more energy-dense foods. Generally high ED equals high palatability and *vice versa* (Drewnowski, 1999). Intense sweeteners may represent an exception to the rule, since they maintain sweetness while reducing ED (Drewnowski, 1999). Results from studies on this topic appear to be controversial. For instance, aspartame has been shown to increase (Blundell & Hill, 1986; Rogers *et al.* 1988), decrease (Rogers *et al.* 1990; Rolls *et al.* 1990), or not to affect (Mattes, 1990; Black *et al.* 1991) hunger or food intake in human subjects. A high inter-subject variability was observed in a study on blood glucose and meal patterns in time-blinded males after an aspartame or carbohydrate preload and included all three of the responses mentioned earlier (Melanson *et al.* 1999*c*). Aspartame ingestion was followed by blood glucose transient declines (40 % of subjects), increases (20 %), or no change (40 %). These patterns were related to the subjects' perception of sweetness of the drink, and were predictive of subsequent intakes. A perception of very sweet coincided with a decline in blood glucose and relatively less suppression of hunger. A perception of much less sweet coincided with an increase in blood glucose and hunger suppression (Fig. 2; Melanson *et al.* 1999*c*). From these experiments it was concluded that the possible effect of lowering ED by replacing the use of simple carbohydrates depends on the sweetness perception of the substitute. If the substitute is not perceived as very sweet, it is perceived as energy, and an increase in blood glucose and hunger suppression follows. When the substitute is perceived as very sweet, it does not suppress hunger. In this respect Holt *et al.* (1991) concluded that satiety power and hedonic preferences were inversely linked. In our studies on artificial sweeteners this was also the case: sweetness perception varied among subjects and showed differences in the hunger suppression responses (Melanson *et al.* 1999*c*).

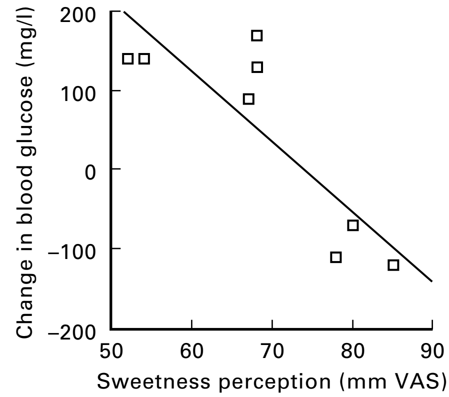

Fig. 2. Relationship between sweetness perception of aspartame and change in blood glucose level in young male subjects. A perception of less sweet coincided with an increase in blood glucose and hunger suppression (Melanson *et al.* 1999*c*). VAS, visual analogue scale.

Macronutrients. With regard to the physiological effects of all macronutrients on EI, Stubbs *et al.* (1999) suggest that different effects from the different macronutrients are caused by a hierarchy in satiety, with protein > carbohydrate > fat, and a priority in oxidation in the same sequence. Our studies showed that these effects occurred simultaneously, i.e. a relatively high satiety and thermogenesis on a diet rich in protein and carbohydrate *v.* a high-fat diet, during a 24 h stay in the respiration chamber (Westerterp-Plantenga *et al.* 1999). This is an example of an increased energy expenditure at rest, implying an increased O_2 consumption and an increase in body temperature, which has shown to be related to satiety (Westerterp-Plantenga *et al.* 1990*b*).

Conclusion

ED was related to EI when the macronutrients fat and carbohydrate determined ED to a large extent, while WW determined ED to a minor extent. Analysis of our data showed that ED does not have a significant relationship with EI when ED was only determined by WW. Long-term effects of ED on EI interact with subject specific behaviour, especially dietary restraint. Then EI was adjusted to a decreased but not to an increased ED in dietary-unrestrained subjects, and EI was adjusted to an increased but not to a decreased ED in dietary-restrained subjects.

Food intake during a meal in relation to energy density and macronutrient composition

Food intake during a meal (2) was studied using cumulative food intake curves (Westerterp-Plantenga *et al.* 1990*a*, 2000*a*; Westerterp-Plantenga & Verwegen, 1999) obtained by monitoring eating from a plate placed on a scale built into a table, and connected to a digital computer. They describe and integrate variables of consumption of an *ad libitum* single course meal, i.e. meal size, meal duration, eating rate, change in eating rate, bite size, and bite frequency (Westerterp-Plantenga *et al.* 1990*a*, 2000*a*; Westerterp-Plantenga & Verwegen, 1999). In one set of

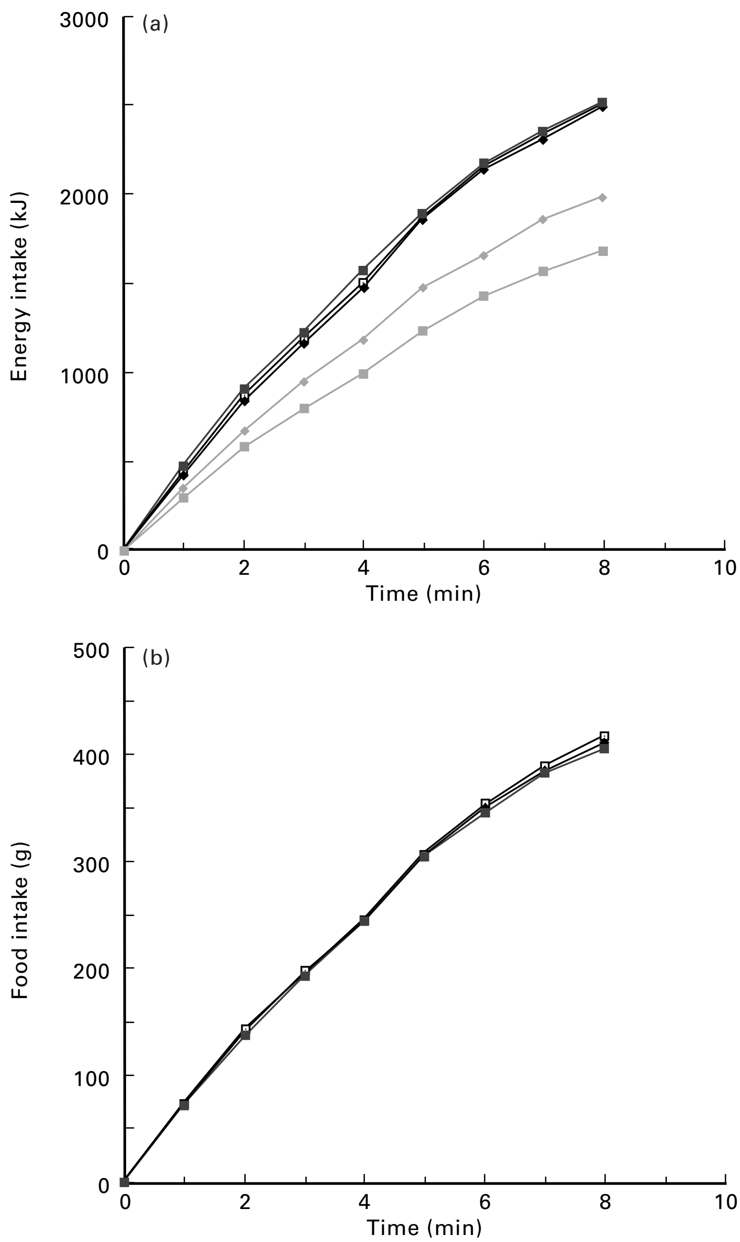

Fig. 3. Example of cumulative food intake in kJ (a) and in g (b) over time of five similar meals differing only in energy density and macronutrient composition. Subjects were normal weight women. Carbohydrate:protein:fat: high carbohydrate, 70:10:20; high protein, 50:30:20; high fat, 50:10:40 (Westerterp-Plantenga, 1990*a*, 2000*a*). (a): –□–, 6·1 kJ/g, high carbohydrate; –◆–, 6·1 kJ/g, high protein; –▩–, 6·1 kJ/g, high fat; –◇–, 4·8 kJ/g; –▨–, 4·0 kJ/g. (b): –□–, 4·0 kJ/g; –◆–, 4·8 kJ/g; –▩–, 6·1 kJ/g.

experiments the ED of an otherwise familiar meal was covertly changed from 4·8 kJ/g to 6·1 kJ/g by replacing some of the food by tasteless protein or carbohydrate powders or by a 'beurre manié'. A beurre manié is a cold mixture of oil with a little flour that can be added to a warm sauce just before serving, without affecting the taste of the sauce. This resulted in a change in macronutrient compositions from 55:15:30 % energy (carbohydrate: protein:fat) to 50:10:40 (high fat), 70:10:20 (high carbohydrate), 50:30:20 (high protein) % energy (Westerterp-Plantenga *et al.* 1990*a*).

In another set of experiments ED was decreased to 4·0 kJ/g by adding 20 g fibre (guar gum) to the meals with the basic macronutrient composition (55:15:30 (carbohydrate:protein:fat)).

A covert change in ED of an otherwise familiar meal from 4·8 kJ/g to 6·1 kJ/g caused no change in the cumulative intake curve variables (Westerterp-Plantenga *et al.* 1990*a*). In addition, the shape of the individual cumulative food intake and satiation curves showed very little variability despite experimentally energy-enriched meals (Fig. 3; Westerterp-Plantenga *et al.* 1990*a*, 2000*a*). Moreover, we found that with meals with the basic macronutrient composition, ED was decreased to 4·0 kJ/g by adding 20 g fibre (guar gum), the amount eaten (g), meal duration, and eating rate did not change. However, after the energy-enriched lunch meals, as well as after the energy-diluted meals with fibre, subjects reported feeling more satiated in the afternoon, skipping their afternoon snacks and showing a longer intermeal interval from lunch to dinner (Westerterp-Plantenga *et al.* 1996*b*, 2000*a*).

The effect of energy density on energy intake during a meal is mediated by conditioning

From these observations we conclude that during a meal, subjects mainly monitored their food intake by weight of the food consumed over time. No changes in cumulative food intake variables were shown in relation to ED (4–6 kJ/g), macronutrient composition and fibre content of a meal within a certain range. However, it was also shown that a change in EI achieved this way showed compensatory effects on the subsequent meal interval and meal size in certain cases (Westerterp-Plantenga *et al.* 1996*b*, 2000*a*).

Similar results from subjects monitoring weight of food rather than energy content of food during a meal were reported by Bell *et al.* (1998). In a study by Yeomans (1996), however, it appeared that palatability interacted with monitoring weight of food intake: increased palatability by adding a small amount of oregano increased weight of food intake and decreased palatability by addition of excess oregano tended to decrease food intake. Given the previous observation that subjects did not monitor EI at least during a first encounter with a meal (Westerterp-Plantenga *et al.* 1990*a*), it was hypothesised that conditioning might take place in order to determine portion size in relation to the energy content of the meal. Since most meals are familiar, conditioning of energy content might have taken place this way. Some evidence for this, at least in dietary-restrained subjects, has been obtained when the subjects were asked to estimate their forthcoming ingestion of a familiar meal. Accuracy appeared to be positively correlated to dietary restraint. While eating an unfamiliar meal this (unconscious) learning aspect of eating behaviour was not yet present, but it was achieved during the second confrontation with the unfamiliar meal (Westerterp-Plantenga *et al.* 1992*a*). Moreover, when diet-induced thermogenesis was assessed under these circumstances, it was significantly greater in the first encounter with the unfamiliar meal, compared with the diet-induced thermogenesis of the encounter with the familiar meal, and also when compared with the diet-induced thermogenesis of the second encounter with the unfamiliar meal. It appears that the facultative part of the diet-induced thermogenesis had increased due to a higher alertness during the first encounter with the unfamiliar meal (Westerterp-Plantenga *et al.* 1992*b*). In addition Spiegel (1973) concluded that at a first encounter, subjects failed to compensate for changes in the ED of a preload. However, when she performed more experiments on consecutive days (2–5 d) compensation improved up to 87 %, albeit not in all subjects (Spiegel, 1973).

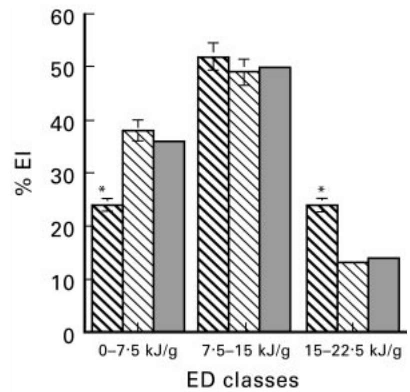

Fig. 4. Percentages of energy intake (EI) from different energy density (ED) categories of food in women. ▧, Obese women; ▧, normal weight women; ▦, guidelines. Values are means with standard deviations shown by vertical bars. Mean values were significantly different from values for the normal weight women, and from the guidelines: $^{*}P < 0{\cdot}015$ (Westerterp-Plantenga *et al.* 1996*a*).

Conclusion

With regard to the effect of ED on EI during a meal, conditioning might play a role. This has been generalised in that portion sizes appear to be culturally related to the food types (Westerterp-Plantenga *et al.* 1996*a*). However, in the course of the day compensatory responses, e.g. to increased ED or to increased fibre contents have also been observed.

Energy intake adjustment to energy density depends on energy requirements

To assess the effect of ED of foods on food choice and portion size (3), we examined EI in relation to ED of foods in obese and non-obese women (Westerterp-Plantenga *et al.* 1996*a*).

From sixty-eight subjects (thirty-four obese and thirty-four non-obese women, matched for age 20–50 years) controlled food intake diaries of two weekdays and one weekend day were analysed. The obese women showed a food intake distribution over three classes of ED of foods, i.e. 0–7·5 kJ/g, 7·5–15 kJ/g and 15–22·5 kJ/g of 24, 52 and 24 % energy respectively, with a macronutrient composition 39:17:44 (carbohydrate:protein:fat) % energy. In the non-obese women the food intake distribution over these three classes was 38, 49 and 13 % energy, with a macronutrient composition of 46:17:37 (carbohydrate:protein:fat) % energy. The distribution in the obese women was significantly different from the values of the non-obese and from the Dutch food guidelines values (Fig. 4; Westerterp-Plantenga *et al.* 1996*a*). Energy intake per meal increased from the first to the third meal of a day: % energy from fat increased and % energy from carbohydrate decreased. The intake of the non-obese women was: breakfast 1·2 MJ, 18 % energy from fat, 65 % energy from carbohydrate; dinner 4·1 MJ, 42 %

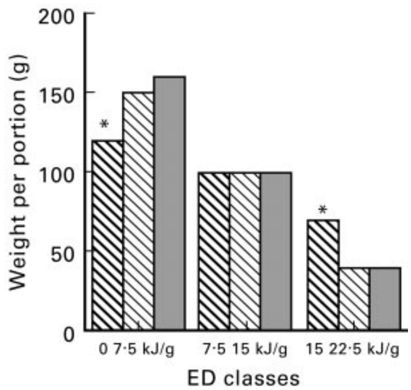

Fig. 5. Mean weight per portion from the different energy density (ED) categories in women. ▧, Obese women; ▧, normal weight women; ▤, guidelines. Mean values were significantly different from the values for normal weight women and from the guidelines: *$P <$ 0·015 (Westerterp-Plantenga *et al.* 1996*a*).

energy from fat, 40 % energy from carbohydrate. The intake for the obese women was: breakfast 1·3 MJ, 38 % energy from fat, 45 % energy from carbohydrate; dinner 4·5 MJ, 46 % energy from fat, and 37 % energy from carbohydrate. With regard to portion sizes it appeared that the obese women took larger portions of food with a high-ED than the non-obese did, and also larger than standard sizes (Westerterp-Plantenga *et al.* 1996*a*; for standard portion sizes see Hulshof *et al.* 1992). Likewise, the obese women took smaller portions of food with a low ED in comparison with the non-obese and in comparison with the standard sizes. In the non-obese, portion sizes were almost standard portion sizes (Fig. 5; Westerterp-Plantenga *et al.* 1996*a*).

For individuals with different energy needs, e.g. normal weight *v.* overweight and obese, portion size, ED and meal frequency play a role in attempts to achieve energy balance. The result is a distribution of EI over three distinguishable ED categories. In order to consume a certain amount of energy during a day a certain weight of food needs to be consumed, which cannot be too large because of stomach filling. This was achieved by a relatively large consumption of food (50 % total daily EI) from the ED category of 7·5–15·0 kJ/g in the obese as well as in the non-obese. These observations can easily be understood because most of the food items belonging to this ED category are staple foods like bread, potatoes, rice and spaghetti. Such products are rich in carbohydrate, and with a 50 % energy consumption from this category, a large part of the daily carbohydrate intake will be reached. Any adjustment of EI to ED must then be achieved by varying intakes in the lower and higher ED categories.

The obese women consumed 24 % energy from the lowest ED category (14 % energy less than the non-obese) and 24 % energy from the highest ED category (11 % energy more than the non-obese). Physiologically this seems a perfect adjustment, and we cannot conclude that the obese women showed a lack of sensitivity to ED, e.g. to a physiological regulation mechanism. For the obese women it might be easier to choose products with a relatively lower weight and high ED, as they showed in the relatively large portions of high-ED foods and relatively small portions of low-ED foods. In addition, from experiments by Drewnowski *et al.* (1992) it is known that the obese people like high-fat foods (belonging to the third category) better than other foods, which results usually in a relatively higher fat:carbohydrate ratio and in those consuming high-ED food.

The non-obese women consumed 38 % energy from the lowest and 13 % energy from the highest ED category. They had portion sizes and a macronutrient composition that did not differ significantly from the composition based on the Dutch food guidelines (Voorlichtingsbureau voor de Voeding, 1992). With regard to the variation of portion sizes in relation to ED of the food, Green *et al.* (1994) reported that in healthy non-obese males, portion size was adapted to a certain extent to ED of snacks of 7·6–16·5 kJ/g. The non-obese as well as the obese women showed a clear pattern of energy and macronutrient intake during the day. EI as well as fat intake increased during the day and carbohydrate intake decreased, albeit that the % energy from fat and % energy from carbohydrate at the start and at the end of the day were different between the obese and non-obese subjects. De Castro (1987) showed the same pattern. The temporal switch from % energy as carbohydrate to fat occurred earlier in the day in the obese subjects, and more gradually in the non-obese subjects. In addition, the obese ate more at their evening meal than the non-obese did (Westerterp-Plantenga *et al.* 1996*a*).

From these analyses some suggestions for weight-reduction diets may be made. First, consumption of high-ED food could be replaced by consumption of low-ED food by switching from the highest to the lowest category, in order to achieve the ED distribution which is shown by the non-obese as well as by the guidelines. Second, considering the energy and macronutrient intake pattern over 1 d, interventions would have relatively bigger effects in the afternoon and evening, when usually the relatively higher-ED foods appear to be consumed. Both dietary suggestions imply a conscious adjustment to eating more food of low ED and less food of high ED. This may be necessary in all obese subjects, and with regard to prevention of obesity, to vulnerable (i.e. overweight) subjects, in order to maintain body weight at a healthy level in subjects with a sedentary lifestyle.

Concluding remarks

In conclusion, ED was related to EI when the macronutrients fat and carbohydrate determined ED to a great extent, and while WW determined ED to a minor extent. ED did not have a significant relationship with EI when ED was only determined by WW. EI was positively related to WW in the food, i.e. when the water was part of the food. ED was negatively related to the water intake of total consumption. When water intake was the main determinant of the ED, there was no relationship between EI and ED.

Long-term effects of changes in ED on EI interact with subject-specific behaviour, especially dietary restraint. Then EI was adjusted to a decreased but not to an increased ED in dietary-unrestrained subjects, and to an increased but not to a decreased ED in dietary-restrained subjects.

Estimation of prospective EI for a single meal probably takes place unconsciously and appears as a conditioned effect. This has been generalised in that portion sizes appear to be culturally related to the food types. However, in the course of the day compensatory responses, e.g. to increased ED or to increased fibre contents have been observed.

Food choice adjustment to ED categories appeared to interact with energy requirements, e.g. the obese show a different distribution of food intake from different ED categories compared with normal weight subjects.

With regard to the treatment of obesity, a conscious shift in food choice of high-ED foods to low-ED foods is recommended.

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