Functional food science and behaviour and psychological functions

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Abbreviations: DHA, docosahexaenoic acid; MSG, monosodium glutamate; SPE, sucrose polyester.
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Abstract

The impact of ingesting various foods on psychological and behavioural functions is a topic of both interest and concern to the general public. In this article, the scientific literature concerning demonstrated cause-and-effect relationships is reviewed, beginning with methodological considerations specific to the quantification of particular behaviours and psychological events. The essential function of food is to satisfy hunger and the need for essential nutrients. The contributions of macronutrients to appetite and satiety are described, as well as their impact on metabolism and energy balance. Functional properties of macronutrient substitutes (high-intensity sweeteners, fat replacers) and flavour enhancers are examined in relation to their contribution to hunger, satiety, and energy balance. The effects of foods and individual nutrients on the performance of diverse psychomotor tasks are studied with consideration given to the various validated quantitative tools used to assess behaviour. The effects of food components on activation, sedation, and affective states such as dysphoria are also reviewed, with special attention given to brain function and neuroactive substances such as serotonin and the endorphins. The case of hyperactivity in children is given special emphasis with reference to the potential influence of sugar and food additives. Safety issues related to food constituents and additives are discussed. Finally, a set of criteria is proposed for the evaluation and elaboration of studies in the behavioural and psychological fields, along with suggestions for future research.

Behaviour: Mental state: Mood

1. Overview

Human ingestive behaviour can be influenced by a number of factors extrinsic to physiological requirements or the nutritional value of individual dietary components. To the extent that certain foods confer additional, and sometimes unexpected, health benefits, they are, according to today's terminology, recognized as 'functional', and are of increasing scientific interest. Public attention is easily captured by claims in the popular press that behaviour is influenced by diet. However, supportive scientific evidence has generally been weak and the data often over-interpreted. At this point, what is needed are rigorously controlled laboratory and field investigations to examine the validity of an ever-increasing array of anecdotal observations.

While biological end-points can be considered universal (e.g. decrease in blood cholesterol, protection from carcinogens), behavioural and psychological end-points can often be culture-specific. Therefore, a food considered to be functional in one society can be less functional or, indeed, not even recognized as such in another. Although foods with diverse functions are known and used in a multitude of cultures throughout the world according to long-standing traditions, the present report focuses exclusively on studies involving Western populations and is limited to describing food functionality in this context.

2. General methodological considerations

The effects of foods and food constituents on behaviour, emotional state, and cognitive performance are typically subtle. Sensitive tests and measures are required to identify, operationalize, and measure behaviours associated with nutrient intake and to uncover causal relationships. From an experimental design standpoint, dose–response trials are indispensable to demonstrate, convincingly, true specificity. Very little can be learned regarding the quantitative effects of a taste stimulus following exposure at one single concentration. Qualitative effects also tend to change with changing stimulus concentrations, particularly with food stimuli, where both the dose (i.e. amount) and the extent of exposure are manipulated.

Interpretation of behavioural effects will necessarily be linked to the time frame of the experiment. The rate, intensity, and temporal pattern of responses are functions of experimental duration. Acute biochemical changes require immediate observation, whereas the adaptation, learning, and tolerance that can surface during chronic treatments are not likely to be apparent in short-term studies.

Outcomes also depend, not surprisingly, on the nature of the sample population. Subjects can be selected or grouped to control for a variety of factors including body size (i.e. by BMI), percentage body fat, dietary habits, weight history, food preferences, and demographics. Questionnaires and personal interviews can be used to isolate individual characteristics or to study certain subjective experiences such as desire to eat, food palatability, and general mood state. Nominal scaling methods such as rank order, fixed-point, multidimensional, and visual analogue are frequently employed to assess hedonics and levels of hunger, appetite, and satiety (Rolls & Hetherington, 1990).

It should be borne in mind that physical characteristics alone are probably not a sound basis for delineating subject groups (Spitzer & Rodin, 1981). Personal experience, as well as attitudes toward beliefs about food, also markedly influence eating behaviour (Aaron et al. 1994). If determined systematically beforehand, these might serve as criteria when treatment groups are formed (Aaron et al. 1994). Since most individuals tend to have strong beliefs about particular foods, blinding subjects to the experimental variables is necessary. This becomes more critical (and progressively more difficult) as the magnitude of dietary manipulations increases. Of course, blinding is not desirable if the subjects' cognitions and expectations are central to the questions being studied.

Which factors should be considered when characterizing subjects remains controversial; nevertheless, numerous methods are available to aid in classification, including the 'restraint scale' (Herman & Polivy, 1980), which measures concern for dieting and weight fluctuation in general, the 'three-factor eating inventory' (Stunkard & Messick, 1985), which measures dietary restraint, disinhibition, and hunger, and the 'eating disorders inventory' (Garner et al. 1983), which examines attitudes, beliefs, and activities associated with dysfunctional eating behaviour. In addition to physical characteristics, these criteria can be used to classify subjects with the aim of decreasing within-group variation.

Cause–effect relationships between nutrients and behaviour can and should be tested in both experimental and naturalistic settings. There is greater control in the laboratory, whereas free-living conditions tend to be more ecologically valid. Whatever the experimental strategy (direct observation v. verbal report, between- v. within-subjects ('crossover') design) each approach carries certain strengths and certain limitations. For example, certain behaviours are normally private and not easy to observe in any setting. Direct observation offers the greatest accuracy, but is often intrusive and necessarily artificial, whereas obtaining the information by follow-up interview leaves the original behaviour intact. But while an open-ended verbal exchange offers flexibility, it introduces the risk of multiple interpretations. Using a questionnaire with a written set of fixed alternatives imposes structure, but it may prove leading and leave subjects feeling constrained and limited.

To study the relationship between nutrients and mood state, numerous standardized scales and questionnaires such as the 'profile of mood states' (McNair et al. 1971) have been developed and validated in order to score particular psychological states. Examining the relationship between self-reported mental states and objective laboratory measures of performance allows the experimenters to use objective performance as a behavioural index of nutrient effects.

2.1. Ensuring the reliability of food intake data

Reliable food intake data are a precondition for establishing the validity of experimental results. The standard methods of determining food intake are:

(1) indirect determination based on group consumption

data, inspection of family budgets, larder inventories, and agricultural production data;
(2) estimation by recall of food consumed over the last day, week, month, or longer;
(3) measurement and recording of food intake as eaten.

Validation of food intake measurements is the main issue. Data obtained via 'dietary recall' and 'diet records' represent food intake at an individual level. The latter method requires subjects to record types and amounts of all foods consumed over a given time interval, while the former uses the subjects' report of intake over the previous 24 h period or the report of customary intake over the previous week or during the past year(s); i.e. a diet history. Food models, volume models, and photographs can help to recall the amounts consumed. Alternative methods include the 'double portion' technique, in which subjects have to collect, for every food item consumed, an equivalent amount for subsequent analysis, or supplying subjects with their daily food ration, measuring the quantity and quality of the food in the laboratory, and then instructing the subjects to consume only the foods provided and to return any left-overs.

Information on the quality of food consumption will be closer to the real life situation in the method of dietary recall than when food is supplied. Conversely, the quantitative method (supplying food) is more accurate than relying on dietary recall. Generally, the subject's energy intake and expenditure should be in balance, but this is very difficult, if not impossible, to check. Sources of error include poor memory, inaccurate estimation of amounts, and wishful thinking. The latter is typical of overweight people who systematically 'under-report' and underweight people (e.g. anorexics) who 'over-report' (Westerterp et al. 1992). In addition, when respondents are required to write down, weigh, or measure what they eat, they may alter their usual dietary habits to make recording easier or to hide their habits. Intermittent energy restriction, i.e. dieting, also is a significant factor in the reduced energy intake reported in overweight people (Ballard-Barbash et al. 1996) and efforts should be made to take it into account.

The length of the observation period is primarily determined by the day-to-day variability expected and the level of accuracy desired. According to Basiotis et al. (1987), to achieve a level of precision of 10 % in a single individual, record-keeping must be maintained for a minimum of 4 weeks. Comparing the dietary record, dietary recall, and the double-portion technique with bomb calorimetry in males spending 1 year on an Antarctic base, Acheson et al. (1980) found that the dietary record method underestimated the energy intake by 7 % on average compared with the analysis of duplicate meals by bomb calorimetry. Errors of over 20 % were found in the energy intake determined by dietary recall. With respect to underreporting, Martin et al. (1996) found the correlation between reported energy intake and expenditure to be only 0·46. Body weight, BMI, height, length of time in the dietary trial, and percentage of energy from fat and carbohydrate were not significantly associated with the accuracy of reporting. Westerterp-Plantenga et al. (1996a,b) found that, after allowing for a deviation of

approximately 10 %, energy intake could be estimated using a computer simulation model (Westerterp *et al.* 1995).

Data on energy intake have been compared with data on energy expenditure as measured by the doubly-labelled water technique, which measures energy expenditure under normal living conditions with an accuracy of 1–3 % and a precision of 2–8 %. Under-reporting, as compared with energy expenditure measured by the doubly-labelled water method, has been reported (e.g. Westerterp *et al.* 1992). A good match between energy intake and energy expenditure was obtained by Sjødin *et al.* (1994) when energy balance was examined in cross-country skiers using doubly-labelled water and dietary records. This study was performed in a training camp where the dietary records were kept by dieticians who were continuously present. Matching energy intake with energy expenditure is also possible when subjects are fed in a respiration chamber. Schrauwen *et al.* (1995) concluded that it takes a 3 d stay in the chamber in order to enable the experimenter to correctly adjust intake to expenditure.

3. Functions of macronutrients in relation to appetite

3.1. Overview

Nutrition is the basic function performed by foods, via intake behaviours. In the sense that the periodic intake of energetic substances contributes decisively to appetite and satiety in order to meet bodily needs in a continuous fashion, all foodstuffs are functional. Intake is stimulated by sensory, physiological and social cues, and satiation and satiety are the result of a cascade of cognitive, sensory, and metabolic (post-ingestive and post-absorptive) signals.

The four macronutrients, carbohydrate, protein, fat and alcohol, have clear effects on appetite, metabolism, satiation (sensory and digestive signals that bring the meal to an end) and satiety (state of fullness which follows a meal). These effects depend on the general subject characteristics including age, sex, ethnicity, social stratification, and education, as well as physical features such as body weight, BMI, body composition, degree of dietary restraint, and circadian rhythms.

3.1.1. Ethnic, educational, and social determinants. The distribution of macronutrient intake differs among countries and cultures. Extreme variations in human food selection can occur in different geographical regions. Nevertheless, there is a fairly wide range of carbohydrate : protein : fat ratios within which energy balance can be maintained. Carbohydrate intake can range from 3 to 82 % of total energy, fat intake from 6 to 54 %, while protein intake is typically at least 11 %. Within a culture or country, dietary changes take place with changes in food supply. Numerous studies have concluded that along with physical characteristics, the subjects' ethnic, educational, and social background has an important influence over the macronutrient composition of their daily intake.

3.1.2. Circadian rhythms. Under normal circumstances, energy and macronutrient intakes follow a circadian pattern, with breakfast being relatively high in carbohydrate and dinner being relatively high in fat. This appears to hold true for lean as well as obese subjects (Kant *et al.* 1995).

Variation in macronutrient intake within meals is mediated by macronutrient- and sensory-specific satiety (Rolls *et al.* 1988; Stubbs, 1995), resulting in a more-or-less stable macronutrient intake over a usual day.

3.2. Effects of macronutrient intake on energy intake, hunger, satiety and metabolism

3.2.1. Fat intake in relation to energy balance. Dietary fat is the main determinant of the energy density of the diet after water. Because it can be stored with minimal additional weight, fat is the primary energy depot in the body. The fat content of the diet has an effect on body fat as a function of the effect of dietary fat on energy intake (Westerterp *et al.* 1996). Adaptation of food intake to the energy density of food is observed as adaptation of portion size in relation to energy density, and as adaptation of quantitative food choice from different energy density categories.

When people change to a diet with a lower or a higher energy density, a change in energy intake has been observed. Duncan *et al.* (1983) reported that energy intake can be nearly twofold higher (12·5 MJ/d) on a high-energy-density diet (6·5 kJ/g) compared with energy intake (6·5 MJ/d) on a low-energy-density diet (3·0 kJ/g) in subjects eating to satiety. Following subjects provided with different diets in which carbohydrate was exchanged for fat, Lissner *et al.* (1987) reported energy intakes of 8·7 MJ/d on a low-fat (15–20 % energy) diet, 9·8 MJ/d on a medium-(30–35 % energy) fat diet, and 11·4 MJ/d on a high-(45–50 % energy) fat diet. In both cases, there was little compensation with respect to energy intake *vis-à-vis* the type of diet during the 14 d observation period. The subjects tended to be in energy balance on the medium-fat diet, lost weight on the low-fat diet and gained weight on the high-fat diet. Kendall *et al.* (1991) provided subjects with a low-(20–25 % energy) fat and a control (30–35 % energy as fat) diet over a period of 11 weeks and, again, energy intakes were lower (7·6 *v.* 8·6 MJ/d) and weight loss greater (2·5 *v.* 1·3 kg) on the low-fat diet. However, there was a significant increase in energy intake over the 11-week period consequent to the low-fat diet, while intake did not change significantly in relation to the control diet. The preceding studies suggest that the fat content of the diet has an effect on body fat as a function of the effect of dietary fat on energy intake.

3.2.2. Fat and carbohydrate intake in relation to satiety. A number of studies have shown that dietary fat has a relatively weak effect on satiety, and that this tends to favour overfeeding (Blundell & Burley, 1992). Comparing the satiating effects of fat and carbohydrate, Rolls & Hammer (1995) concluded that there is a small, but significant, insensitivity to energy from fat. Perhaps not only insensitivity to energy from fat, but also masked sensory perception of fats in some solid foods, may explain why fat promotes overfeeding. Many sweet, high-fat foods in which the fat is masked by sugars are commonly identified as carbohydrate-rich (Drewnowski & Schwartz, 1990). The sweet desserts that seem to be especially favoured by obese women (Drewnowski *et al.* 1992) may not even be recognized as high-fat foods.

3.2.3. Relative levels of fat, carbohydrate and protein intake in relation to satiety and metabolism.

Macronutrient selection and compensation and diet-induced changes in nutrient balance theoretically occur to the extent that fat, protein and carbohydrate have independent effects on appetite regulation or differing satiating efficiencies. In studies of up to 2 weeks duration under free-living conditions (de Castro, 1987), as well as in laboratory studies (Blundell & Burley, 1992), protein has been shown to be the most effective at suppressing energy intake, followed by carbohydrate, with fat having the weakest effect on satiety.

Short-term changes in nutrient metabolism result from changes in the macronutrient composition of the diet (Verboeket van de Venne & Westerterp, 1991) and can affect post-ingestive satiety as well. One physiological adaptation that appears is the approach of RQ values towards food quotient values (Shetty et al. 1994), that is, where the profile of metabolic fuels utilized by the body changes with the composition of the diet.

The hierarchy in the immediacy with which recently ingested macronutrients are metabolized is protein – carbohydrate – fat (Stubbs, 1995). The same hierarchy appears in satiating efficiencies of the macronutrients, and this is believed to have a metabolic component. This view is supported by results from diet-induced thermogenesis measurements in normal-weight men and women made during and after the consumption of a lunch offered on three different occasions in a full-fat version, an identical but reduced-energy–reduced-fat version, and in an iso-energetic (to the full-fat lunch type)–reduced-fat version. Subsequent RQ values corresponded to the food quotients such that the RQ was significantly lower after the full-fat lunch (low food quotient) than after the two reduced-fat lunches (higher food quotient) (Westerterp-Plantenga et al. 1997b). Moreover, satiety scores were positively related to the magnitude of diet-induced thermogenesis expressed as an absolute increase in metabolic rate during and after the meal.

It remains difficult to distinguish between macronutrient- and sensory-dependent food selection, as well as to distinguish between macronutrient-specific satiety and sensory-specific satiety, but macronutrient-specific satiety probably has a sensory-specific component. The mechanism that produces sensory-specific satiety is dependent primarily on activity in the processing systems for olfactory and taste information in the brain, whereas macronutrient-specific satiety is more probably an interaction with gastrointestinal feedback or energy monitoring signals (Rolls & Rolls, 1997).

3.2.4. Alcohol intake and satiety.

Not much is known about the effects of alcohol on hunger, satiety, and food intake in relation to body weight. Community survey studies tend to support the anecdotal evidence showing that in moderate alcohol consumers, total energy intake increases when alcohol is introduced into the diet (e.g. Rissanen et al. 1987). This suggests that energy derived from alcohol is not recognized or is not regulated by the body. Appetite remains unchanged or even heightened and, therefore, there is no compensatory decrease in food intake. However, the epidemiological evidence suggests that women who consume moderate amounts of alcohol tend to have a lower BMI than abstainers (Colditz et al. 1991). Studies conducted in a metabolic ward suggest that an addition of a large amount of alcohol per day results in no additional weight gain (Priola & Lieber, 1972). Despite speculation that alcohol might be metabolized less efficiently than other substrates, with a large amount of energy being lost as heat during so-called futile cycles, numerous metabolic studies have failed to show greater heat production following alcohol v. carbohydrate or fat ingestion (e.g. Sonko et al. 1994).

Foltin et al. (1993) measured the effect of ethanol on subsequent food intake within a metabolic ward, concluding that alcohol-derived energy appears to be under normal physiological regulation, decreasing food intake in a manner similar to that of isoenergetic carbohydrate sources. This suggests that alcohol is as satiating as carbohydrate. Other dietary studies have shown that when alcohol is included in the diet, there is little or no reduction in food intake, unless physiological control is in part over-ridden by social and environmental factors (de Castro & de Castro, 1989). More recently, Rumpler et al. (1996) investigated the effects of an isoenergetic substitution of ethanol for dietary carbohydrate on energy expenditure and body composition, and showed that, on an energy basis, ethanol and carbohydrate are utilized with the same efficiency. However, Tremblay & Saint-Pierre (1996) reported that when alcohol is consumed during a meal, its energy content is not compensated for by an equivalent decrease in energy intake from other macronutrients and thus, total energy intake increases when alcohol is consumed. Thus, a discrepancy remains between the epidemiological data which tend to indicate an inverse relationship between alcohol consumption and body weight, and well-controlled metabolic studies, which do not show this effect.

3.3. Functional properties of macronutrient substitutes

Nowadays, various commercially-produced foods claim to influence appetite and satiety in 'new and beneficial' ways. To this end, the functional aim of macronutrient substitutes (e.g. high-intensity sweeteners and fat-replacers) is to help consumers improve their diet by giving them an opportunity to reduce sugar (17 kJ/g) and/or fat (38 kJ/g) intake, with the short-term objective of controlling energy intake, and the long-term objective of weight loss or weight stability (Bellisle & Perez, 1994). The studies that have been carried out to test their efficacy have varied widely in design and scientific merit.

3.3.1. The preload paradigm.

In studying the influence of reduced-energy substitutes on food intake and energy regulation, a first course 'preload' (i.e. a food or drink manipulated according to energy and/or macronutrient content) is typically ingested by volunteers, with subsequent food intake serving as the dependent variable. One or several hours following ingestion, the subject's spontaneous intake is measured under laboratory conditions, and the differential carry-over satiety effects of preload ingestion on subsequent eating behaviour are determined (de Graaf et al. 1992). Ratings of subjectively perceived hunger or satiety, desire to eat, or prospective intake are obtained following the intake of the preload (Blundell & Green, 1996).

3.3.2. The issue of compensation. Behavioural responses to energy-reduced substitutes for regular foods can differ as a result of learning based on repeated exposure (Booth *et al.* 1976). Learned adaptation may take anything from a few days (Louis-Sylvestre *et al.* 1987) to several months (Prewitt *et al.* 1991). Various levels of compensation have been reported over the course of a few hours following the ingestion of low-energy, low-sugar, or low-fat loads (Booth, 1991; de Graaf *et al.* 1992). Stimulation of eating has also been observed after the oral intake of sweet-tasting foods and drinks containing intense sweeteners (Blundell & Hill, 1986), although this effect remains controversial (Rolls, 1991).

Compensation remains the most critical issue *vis-à-vis* the response to macronutrient substitutes. In studies on possible energy intake compensation after low-fat diets, complete macronutrient intake compensation has not been shown (e.g. Blundell *et al.* 1991, 1993). In everyday life, it is nearly impossible to compensate specifically for nutrients since most foods are of composite nutritional content (Beaton *et al.* 1992). Compensation appears more likely to be observed in male (*v.* female) subjects, and more apparent when the energy difference between the regular and the energy-reduced stimulus is large. Energy compensation also depends on dietary restraint, duration of the use of the replacer, and on whether the fat is replaced in snacks or in meals. A 6-month follow-up of adults consuming prescribed diets showed that a change in the body fat mass was observed only when total energy intake was also changed (Westerterp *et al.* 1996).

It has been suggested that replacement of sugars by intense sweeteners might theoretically lead to a net increase in the proportion of fat in the diet (Beaton *et al.* 1992). Such an effect would make intense sweeteners counter-functional and deserves to be investigated under carefully-controlled conditions. Thus, it is possible, but not assured, that intense sweeteners, as a functional ingredient in palatable foods with reduced energy, could aid in energy control and weight-reduction (Rolls, 1991).

3.3.3. Highlight: sucrose polyester. A particularly interesting class of non-absorbable fat replacers are the so-called sucrose polyesters (SPE). The main questions that have been addressed involve the effects on energy intake and food choice in various groups of subjects who differ with respect to eating behaviour. When SPE replaced conventional fats in the diet of homogeneous groups of lean men, for example, energy, but not macronutrient, compensation was observed (Rolls *et al.* 1992). When the behaviour of subject groups characterized by their level of 'dietary restraint' (limitation of food intake in terms of meal size, meal frequency, and food choice) was contrasted with appropriate controls, normal-weight, 'unrestrained' men compensated accurately for given energy preloads, regardless of the nutrient composition, whereas normal-weight, 'restrained' men did not exhibit such orderly energy intake compensation. However, neither normal weight nor obese females, regardless of whether they could be characterized as restrained or unrestrained eaters showed orderly compensation for energy preloads (Rolls *et al.* 1994).

No difference in energy intake compensation between restrained and unrestrained eaters has been found with low-fat lunch meals (Chapelot *et al.* 1993) nor with energy-reduced lunches (Westerterp-Plantenga *et al.* 1994). Hulshof *et al.* (1995) found no energy intake compensation in women in the short term, but in men they found a tendency to compensate. When the fat was replaced by SPE, energy intake compensation was less than 50 %, but when the fat was replaced by water, it was 66 %. Employing a medium-term (12 d) protocol, de Graaf *et al.* (1996) reported that less energy was consumed per day when fat was replaced by SPE; i.e. the percentage of energy from fat decreased from 43 % to 32 % and this was accompanied by a corresponding decrease in body weight.

Westerterp-Plantenga *et al.* (1997*a*) reported that in dietary unrestrained and post-obese, restrained subjects, a significant reduction in energy intake and changes in macronutrient compositions were achieved by replacement of fat by SPE in snacks. In normal weight, restrained women, significant energy intake reductions and changes in macronutrient compositions were also achieved by similar meal manipulations. In neither case were deviations in hunger and satiety noted.

Cognitive influences have also been investigated with regard to the energy or macronutrient content of test meals. Some workers have shown that subjects can be misled by information regarding fat content (Caputo & Mattes, 1993), while in other cases, no effect of true or false information has been observed (Chapelot *et al.* 1993).

3.4. Modulating food intake through palatability enhancers: the case of monosodium glutamate

Palatability is not only a vital issue when considering how to limit food intake, it is also critical when attempting to augment intake in populations at risk of nutritional deficiency. Foods are heated, salted, spiced, and decorated, all with the objective of enhancing palatability. However, one of the advantages of a non-traditional 'palatability enhancer', such as monosodium glutamate (MSG), is its capacity to augment food intake without noticeably changing the sensory aspects of the food (Yamaguchi, 1991). Activation of discrete sensory receptors on the tongue for the 'umami' taste is believed to be responsible for the stimulating effects of MSG (Yamaguchi, 1987).

Several short-term studies have shown a clear increase in intake when food palatability is enhanced. However, as very few studies have investigated the effects of manipulating test foods over the course of many days or weeks, the long-term potential of MSG remains unclear. There is some indication that while responsive persons are likely to eat more when exposed to a sudden improvement of diet, after a few days of exposure, intake generally stabilizes at a level that does not lead to body-weight gain (Rodin & Slochower, 1976). Adding MSG to several foods typically encountered in a Western diet has a positive action on ratings of palatability obtained in classic sensory evaluation tests. Adding MSG can lead to increased intake of many foods on first exposure (Beauchamp *et al.* 1987) and, when added on repeated occasions, apparently contributes to the acquisition of a liking for the MSG-containing foods (Bellisle *et al.* 1991). Sweet-tasting substances (Perez *et al.* 1994; Reid & Hammersley, 1995) and MSG are the only palatability

agents which have been shown to influence food intake beyond the immediate ingestion of the palatable food itself. The current challenge is to ascertain how manipulating the palatability of various foods over the long term affects intake. MSG is an efficient way to influence within-meal food selection (Bellisle *et al.* 1996).

4. Foods and cognitive performance

4.1. Overview

In general, the literature on the effects of foods and food constituents does not cover a wide range of food types or food components. In addition, the measures of cognitive performance used are usually limited to a small number of well-known tasks or tests. There is considerable scope for more and better research using clearly defined nutritional manipulations or nutrients and an extended range of sensitive and relevant cognitive tasks.

Nutritional manipulations shown to influence cognitions include missing meals, dieting and snacking. Macro-nutrients such as carbohydrate and fat have been shown to both impair and improve certain aspects of cognitive performance, as have other food components (e.g. vitamins, glucose and tryptophan). Well-documented effects on cognitive performance have been observed following administration of caffeine and alcohol, although the effects tend not to be as great as those which follow psychotropic pharmaceutical preparations (Hindmarch *et al.* 1991).

4.2. Performance tasks

In principle, a large number of mental or cognitive tasks are potentially able to demonstrate the effects of foods on performance. In practice, however, a limited number of tests have been used. Some of the more frequently used are listed in Table 1.

In general, performance tasks can examine a number of skills or abilities concerning the following functions: perception, memory, attention and arousal, information

processing, accuracy and speed of movement. In addition to the tasks listed in Table 1, other tests which have not been used frequently include digit symbol substitution (information processing, speed and accuracy of encoding), critical flicker fusion threshold (measure of central nervous system arousal), Stroop test (measure of speed of resolution of perceptual conflict), Corsi block tapping (spatial memory), and various types of reasoning (logical, mathematical, abstract). There are also specialized and sensitive tests used in educational work, psycho-geriatrics or in the assessment of neurological impairment. These have not been used with foods but have the potential to detect changes in important functions in response to dietary manipulations.

The tasks set out here usually represent single components which form part of more complex skills and abilities; for example, car-driving ability or operating machinery. In choosing a task, much depends on whether an immediate (short-term) effect of food is expected or whether a chronic (long-term) adaptation to a diet is being examined. Cognitive performance encompasses not only measures of speed (reaction time) but also of processing accuracy (measures of accurate and inaccurate detection), and interventions may elicit changes in function in some or all of these performance components. Recent advances in computer technology have meant that these tasks can be administered in a structured, carefully-controlled fashion, with extremely accurate measurement of reaction time and the rate of correct and erroneous responses.

4.3. Effects of nutritional manipulations on performance

4.3.1. Food v. no food first thing in the morning. It is necessary at the outset to demonstrate that food itself (compared with no food) will influence cognitive performance. A number of studies (see Table 2), beginning with the Iowa breakfast studies (Tuttle *et al.* 1954), have demonstrated that missing breakfast can have detrimental effects on performance in terms of reaction time tasks, spatial memory and immediate word recall (Benton & Sargent, 1992; Smith *et al.* 1994a). While some aspects of memory

Table 1. Functions assessed by cognitive tests

Function	Test	Description
Vigilance (also known as attention), rapid information processing or continuous performance	Bakan test	A series of numbers are presented visually in rapid succession on a VDU screen. The subject (S) has to respond by depressing a key when a sequence of three odd or three even digits is detected.
Reaction time (decision time and movement time)	Simple (SRT) or choice (CRT)	Stimulus appears (visual or auditory) and S must make a single response usually by depressing a key. In CRT one of a number of stimuli may appear and S must make one of two responses (e.g. left hand, right hand) according to the type of stimulus.
Working memory (short-term memory)	Immediate recall	S shown a list of twenty words at a given rate (e.g. 1 per s). At end of presentation S recalls the words.
	Word recognition	S must recognize rather than recall.
Immediate memory	Digit span	S must remember (recall) series of items in forward or reverse order.
Psycho-motor performance (tracking ability)	Pursuit rotor	S must trace a shape (maze) with a stylus under time pressure. Error score computed.
	Tapping task	S must tap in rapid succession to a key.

VDU, visual display unit.

seem to be susceptible to the effects of missing breakfast, other aspects of performance are not affected (Smith et al. 1994a). These studies were all performed on adult subjects but differed in terms of the experimental design and the particular performance measures employed. Studies in children and adolescents show clearer deficits on a wide range of performance tasks following omission of breakfast, with greater effects in under- and malnourished children (Vaisman et al. 1996).

A number of studies have shown that breakfast v. no breakfast (early morning meal) or high- v. low-energy breakfasts cause changes in sustained attention, reaction time and memory. Energy improves performance in all of these and may be related to blood glucose levels, with high-carbohydrate meals producing the best effects.

4.3.2. Effects at midday. When nutritional manipulations are made at midday, performance on attention and reaction time tasks is usually impaired (see Table 3). One study has shown that eating lunch (v. no lunch) worsens performance on attention and reaction time tasks (Smith & Miles, 1986b). A large lunch-time meal contributes to the 'post-lunch dip' in performance. This means that performance on sustained attention tasks is impaired in the early afternoon compared with late morning, an effect that is effectively abolished by administering caffeine.

The obvious differences in post-breakfast and post-lunch psychological effects open the question of the reasons why the same behaviour, that is eating, is followed by contrasting or even opposing consequences. Time of day (circadian biological effect), size of meal or macronutrient selection could all contribute to the observed differences. The post-lunch dip, a clearly undesired effect in Western industrial societies, could be a fruitful area of research for the development of functional foods.

4.3.3. Effects following evening meals. A few studies have examined the effects of meals eaten late in the day. Effects are mixed, with logical memory being improved by a meal, but no changes occurring in sustained attention, word recall or word recognition (Smith et al. 1994b). Visual search under high memory load is impaired by both early and late evening meals (Smith & Miles, 1987). It should be kept in mind that optimal performance is usually seen with the type of meal habitually consumed by the subjects, and any change from the usual nutrient composition normally leads to deterioration. Differences in performance could therefore be ascribed to psychological or physiological phenomena. Moreover, discrepancies are often seen between subjective (rating scales, questionnaires) and objective (cognitive tasks) measures of performance.

4.4. Influence of macronutrient ratios and individual nutrients

A good deal of work has been prompted by the idea that foods varying in the proportions of carbohydrate and protein would influence performance via changes in brain

Table 2. Effect of breakfast (BF) on performance

Reference	Type	Tasks	Effect
Adults			
Tuttle (1950, 1952)	No BF v. BF	RT	poorer
Benton & Sargent (1992)	No BF v. BF	memory: spatial	poorer
		immediate work recall	poorer
Dickie & Bender (1982)	BF v. no BF	arithmetic	no effect
		STM	no effect
Smith et al. (1994a)	(a) BF	sustained attention	no effect
		pulse rate	increased
	(b) BF	free recall	improved
		recognition memory	improved
		semantic memory	no effect
		logical reasoning	impaired
Michaud et al. (1991)	Normal v HE intake at BF	STM, immediate recall	improved (HE)
		concentration	impaired (HE)
Lloyd et al. (1994)	Low fat/high CHO BF v. med/high fat	test battery	improved with high-CHO BF
Children			
Pollitt et al. (1981, 1983)	No BF	problem-solving (MFF)	poorer
		immediate memory (recall of last item-recency)	improvement
Simeon & Grantham-McGregor (1989)	BF v. no BF	verbal fluency and coding	poorer
		numeric digit span backwards	poorer
		MFF test	poorer
Chandler et al. (1995)	BF v. no BF	four tests of cognitive function	no effect
		verbal frequency	poorer
Cueto (1995)	BF v. no BF	STM speed	poorer
		geometric pattern discrimination	poorer
Wyon et al. (1997)	HE v. LE BF	creativity	improved (HE)
		physical endurance	improved
		addition	more errors (LE)
		multiplication	no effect
Connors & Blouin (1983)	No BF v. BF	RT	more errors
		arithmetic test	improved

CHO, carbohydrate; HE, high energy; LE, low energy; MFF, matching familiar figures; RT, reaction time; STM, short-term memory.

Table 3. Effect of lunch on performance

Reference	Type	Tasks	Effect
Lloyd et al. (1994)	high-fat low-CHO (HFLC)/low-fat high-CHO (LFHC)/medium-fat medium-CHO (MFMC)	RT immediate recall rapid information processing	LFHC + HFLC > MFMC no effect no effect
Smith & Miles (1986a,b)	lunch v. no lunch	attention RT	impaired after lunch impaired after lunch
Smith & Kendrick (1992)	large meal (4·18 MJ)	sustained attention	impaired
Spring et al. (1983)	HC v. HP	RT	impaired – HC
Lieberman et al. (1986)	HC v. HP	sustained attention	impaired – HC
Wells & Read (1996)	low energy (HFLC) high energy (LFHC)	Bakan SRT CRT	↑ false alarms – LFHC no effect no effect
Kanarek & Swinney (1990)	low-energy snack (LCS) v. high-energy snack (HCS) +/– lunch	backward digit span attention arithmetic reasoning reading	HCS > LCS lunch – no effect HCS > LCS lunch – no effect HCS > LCS lunch – no effect lunch – >improvement HCS > LCS
Kelly et al. (1994)	LF; HF; LC; HC (H v. L energy intake)	psychomotor	no effect – energy no effect – macronutrients

CHO, carbohydrate; CRT, choice reaction time; HC, high carbohydrate; HP, high protein; RT, reaction time; SRT, simple reaction time.

serotoninergic function (Young, 1991). A number of psychological changes have been predicted from diets varying in carbohydrate and protein content but the evidence is, in fact, quite weak. However, several studies have found that high-carbohydrate meals do tend to produce greater drowsiness, sleepiness and calmness (e.g. Spring et al. 1987).

4.4.1. The carbohydrate–tryptophan connection. The theoretical background linking carbohydrate and serotonin (5-hydroxytryptamine) implies that the dietary effects are mediated by changes in the plasma ratio tryptophan : large neutral amino acids. The argument depends on the extent to which meals vary in carbohydrate and protein content. Circulating tryptophan exists in a free form and bound to blood albumin. After a high-carbohydrate meal (which must contain almost no protein), the insulin that is released causes branched-chain amino acids to be taken up into tissues, particularly muscle. Insulin also reduces the release of non-esterified fatty acids into the plasma; plasma non-esterified fatty acid concentration falls and albumin binding sites are liberated. Consequently, a high-carbohydrate meal elevates the tryptophan : large neutral amino acid ratio in the plasma. This, in turn, favours the uptake of tryptophan into the brain as the amino acids compete for the selective carrier across the blood–brain barrier. Consequently, carbohydrate meals increase brain tryptophan. Since the enzyme tryptophan hydroxylase (*EC* 1.14.16.4) is normally not saturated with its precursor, the availability of tryptophan becomes the rate-limiting step in the synthesis of the neurotransmitter serotonin. The logic of this argument is that high-carbohydrate meals enhance serotoninergic neurotransmission in the brain (Fernstrom & Wurtman, 1972). However, adding as little as 40 g protein/kg to the meal can abolish the 'tryptophan effect' (Teff et al. 1989).

Administering tryptophan should produce similar effects to eating carbohydrate. Lieberman et al. (1983) compared the effects of tryptophan and tyrosine on four performance tasks: simple auditory reaction time, two-choice reaction time, grooved pegboard, and the Thurstone tapping task. The tryptophan treatment differed from tyrosine only on auditory reaction time but neither amino acid produced a response that differed from its own placebo. However, tryptophan did increase subjective ratings of fatigue–inertia and decreased feelings of vigour–activity on rating scales. In other tests, a high-carbohydrate lunch (compared with protein) was found to impair performance on the digit symbol substitution test, with a high starch load linked with slower reaction time but having no effect on a dichotic listening task (Lieberman et al. 1986).

Further studies using high-energy, high-carbohydrate snacks have examined effects on four cognitive tasks: digit span, arithmetic reasoning, reading and attention (Kanarek & Swinney, 1990). In comparison with a low-energy soft drink containing aspartame, a high-carbohydrate snack of yoghurt improved digit span performance (greater recall) and enhanced performance in the attention task (continuous performance) in the late afternoon. Subjects receiving the energy-containing yoghurt (compared with a soft drink) solved more arithmetic problems in a shorter time. The consumption of lunch before testing had no effect on this performance. Lloyd et al. (1996) failed to find differences in objective performance following breakfasts with a low-, medium-, or high-carbohydrate content, but did find that the high-carbohydrate breakfast improved mood by reducing fatigue and dysphoria.

A simple-sugar load improves performance, probably due to a rise in blood glucose. A large carbohydrate meal is likely to produce variable effects on performance, depending on the presence of some protein with the carbohydrate. Although a very-low-protein (less than 40 g/kg) meal will trigger changes in serotoninergic neurotransmission, a usual meal, with a higher protein content, will not elicit the rise in tryptophan.

4.4.2. Dietary fat. Little decisive research has been carried out regarding the effect of dietary fat on performance.

Comparisons of low- and high-carbohydrate and low- and high-fat lunches revealed no effects on psychomotor tasks (Kelly *et al.* 1994) but with *n* 6, the power was obviously low. A subsequent study (Lloyd *et al.* 1994) showed that optimal performance was seen with a medium-fat–medium-carbohydrate lunch, whereas higher proportions of either fat or carbohydrate caused subjects to be more drowsy, uncertain and muddled, impairing cognitive efficiency.

A comparison of four fat–carbohydrate combinations in human trials showed that all diets increased subjective lassitude (Wells & Read, 1996). It was alleged that morning fat caused a greater depression of alertness and mood, but the study design was questionable and effects were weak. Smith *et al.* (1994*b*) showed that a high-fat meal did not affect logical reasoning or vigilance but did produce slower but more accurate performance on selective attention tasks. Little is known about the influence of the level of dietary fat saturation on human subjects, but work by Greenwood & Winocur (1990) has shown that a diet high in saturated fat impairs learning acquisition in rats.

Studies have examined the effect of the fatty acid docosahexaenoic acid (DHA) on visual acuity in term and preterm infants (Carlson *et al.* 1996). There is evidence that DHA is important for normal visual development. Formula feeding provides linoleic acid but not DHA, which is available from human milk. Comparisons of the visual acuity of infants fed with either DHA or linoleic acid for at least 3 months showed a positive relationship between DHA status and visual acuity in infants fed with the DHA-enriched formula (Carlson *et al.* 1996).

4.4.3. Glucose. A substantial number of studies have shown generally beneficial effects of glucose on performance (see Table 4). A series of studies in elderly subjects showed enhanced effects on working (short-term) memory, and similar effects have been demonstrated in young adults (Benton & Sargent, 1992). Following a glucose drink, blood glucose level correlated with improved decision time in a reaction time task (Benton & Owens, 1993). Rising levels of blood glucose were associated with better recall than falling

levels. The glucose-induced improvement was observed across a range of baseline blood glucose levels and, hence, was not the product of hypoglycaemia. Hypoglycaemia was associated with slower reaction times. The higher levels of blood glucose (following a glucose drink) correlated with faster information processing, better word recall, and improvement on the Stroop test.

4.4.4. Dietary choline. As noted earlier, precursors of neurotransmitters in the diet (and then in the plasma) can lead to increases in levels of the neurotransmitter in the brain. Choline is the precursor for acetylcholine. In animal studies, significant improvements in cognitive performance have been seen with choline-enriched diets. In young adults, one study showed an improvement in memory with choline. In elderly people (for whom memory disturbance is often a problem), however, the results have been disappointing. In a review of seventeen studies using choline or lecithin (a major source of choline in the diet), only one study found an improvement of memory in the majority of subjects (Bartus *et al.* 1982).

4.4.5. Vitamins and minerals. In the elderly, cognitive function and measures of intelligence are enhanced by supplementing the diet with pyridoxine, cobalamin, and folic acid (Goodwin *et al.* 1983). Further research is needed to determine to what extent these substances might arrest the decline in cognitive ability in old age. In children, multivitamin supplements have been claimed to produce superior performance on a test battery (Wechsler intelligence scale, non-verbal subscales) (Benton, 1992). However, this is controversial, and two studies have found negative effects (Crombie *et al.* 1990; Nelson *et al.* 1990). Few studies have considered specific vitamins, although Southon (reported in Nelson, 1992) found a positive correlation between plasma ascorbic acid, glutathione peroxidase (*EC* 1.11.1.9) activity, and non-verbal intelligence scores.

One factor that may be important in the interpretation of the results of these studies is the habitual diet of the children concerned. Nelson (1992) has suggested that where the diet is deficient in several nutrients, children may show poorer

Table 4. Effect of glucose on performance

Reference	Experimental situation	Tasks	Effect
Pollitt *et al.* (1983)	children – food deprivation	problem-solving memory	negatively correlated with performance
Owens & Benton (1994)	glucose drink	inspection time	no effect
	blood glucose level	simple reaction time (decision time)	faster with ↑ blood glucose
Gonder-Frederick *et al.* (1987)	elderly	memory	enhanced
Hall *et al.* (1989)	elderly	memory	enhanced
Manning *et al.* (1990)	elderly	memory	enhanced
Lapp (1981)	young adults	memory	enhanced
Hall *et al.* (1989)	young adults	memory	enhanced
Benton & Owens (1993)	young adults	memory	enhanced
Holmes *et al.* (1986)	mild hypoglycaemia	RT	slower
Herold *et al.* (1985)	mild hypoglycaemia	RT	slower
Fourest-Fontecave *et al.* (1987)	mild hypoglycaemia	RT	slower
Langan *et al.* (1991)	severe hypoglycaemia	RT	slower
Deary *et al.* (1993)	severe hypoglycaemia	RT	slower
Benton *et al.* (1994)	glucose drink	rapid information processing (Bakan)	faster with ↑ blood glucose
		Stroop	enhanced with ↑ blood glucose (at start of task)
		word recall	↑ recall with glucose drink

RT, reaction time.

performance on tests of non-verbal intelligence quotient. Differences between studies in developed and developing countries suggest that the extent of the dietary deficiency is important and that supplementation programmes are more likely to produce improved performance in the latter than in the former environment.

4.4.6. Alcohol. Like caffeine, alcohol produces clear effects on cognitive function and can be used as a standard for the comparisons of nutritional or food manipulations. In general, alcohol impairs performance on psychomotor tracking, driving tasks, perception, and sustained attention (Hindmarch *et al.* 1991).

4.5. The case of caffeine

As might be expected, most studies have shown that caffeine use leads to an improvement in most measures of cognitive performance, particularly reaction time, vigilance, memory (speed of retrieval) and psychomotor performance (e.g. Smith *et al.* 1992). It has been suggested that caffeine possesses cholinergic cognition-enhancing properties (in contrast to acetylcholine precursors, cholinergic drugs have marked effects on memory). Caffeine can also improve selective attention, and faster reaction times are probably due to faster central and/or peripheral motor responses. There has been some debate as to whether effects depend on the level of caffeine consumption. Jarvis (1993) demonstrated increased word recall in high-caffeine consumers whereas Mitchell & Redman (1992) found that high consumers performed consistently worse than low and moderate users. Rogers *et al.* (1995) found that the performance in a reaction time task was influenced by caffeine only in high, but not in low, users. Other subgroups of subjects who respond differently to caffeine are high (*v.* low) 'impulsives'. (Impulsivity is a tendency towards spontaneous, sometimes uncontrolled reactions. Impulsive people (impulsives) are identified using questionnaires.) Anderson & Revelle (1982) reported that high impulsives enhance their performance following caffeine, while performance of low impulsives is impaired. High impulsives tended to profit from caffeine only in the morning when their arousal was low. Smith *et al.* (1991) found similar results with regard to group differences, but in this study high impulsives were sensitive to caffeine in the morning as well as in the afternoon.

5. Functional effects of foods on activation or sedation

5.1. Overview

The literature regarding the functional effects of foods on activation and sedation generally focuses on behaviours such as sleep, activity and hyperactivity, as well as several aspects of mood, including feelings of tension, calmness, drowsiness and alertness. The following section considers separately the effects of different food components, especially caffeine and the amino acid tryptophan, the dietary carbohydrate:protein ratio and, with regard to hyperactivity, the effects of sugar and food additives.

5.2. Methods for assessing activation or sedation

Effects regarding activation and sedation, relaxation and tension are often not tested directly, but are subsumed under influences on mood. Since affective states cannot be directly measured, research on mood has to rely on reports by the subject regarding his or her present state. The methods most often used to assess temporal aspects and changes of moods are adjective check lists and visual analogue scales. Adjective check lists are more or less lengthy lists of adjectives which the subject uses to describe his or her present emotional state. Dimensions of moods are typically explored using 'factor analysis' techniques such as visual analogue scales, which basically consist of a line anchored at both ends with the description of an emotional state (e.g. 'extremely angry' – 'not at all angry'). The subject indicates, through a mark on this line, to what extent the description applies to his or her present state.

With regard to sleep, methods include measurement of sleep latency, i.e. the time taken to fall asleep, subjective ratings of sleepiness or related feelings, drowsiness, and related performance measures such as reaction time, vigilance, or tasks requiring sustained attention.

5.2.1. Tryptophan. Behavioural and psychological effects of tryptophan are well-documented and summarized in several reviews (Hill & Blundell, 1988). Sleep and feelings of fatigue are affected by tryptophan intake. In both adults and children, tryptophan reduces sleep latency and promotes feelings of drowsiness and fatigue (Steinberg *et al.* 1992).

5.2.2. Tryptophan, tyrosine, and 'jet lag'. Kits containing pills of tyrosine and tryptophan are currently marketed to combat 'jet lag'. It is thought that these substances could help individuals by adjusting their circadian rhythms after crossing several time zones during airline travel. Because tyrosine is a precursor to the catecholamines, higher plasma levels of tyrosine could stimulate catecholamine release, consequently promoting alertness, while tryptophan promotes sleepiness, as detailed earlier. If tyrosine is taken in the morning and tryptophan is taken in the evening, this might help to synchronize circadian rhythms more rapidly after a major change in the day–night cycle. However, there is no sound experimental evidence to support this hypothesis (Waterhouse *et al.* 1997).

5.3. Carbohydrate v. protein: effects on performance

In accordance with the previously mentioned results on the effects of tryptophan, several studies have found greater drowsiness, sleepiness and calmness after carbohydrate-rich meals compared with protein-rich meals (see Spring *et al.* 1987). However, the differences were not consistent across all subject groups and many mood and performance measures were unaffected by experimental condition. Although lunch and breakfast reportedly have different effects on fatigue or drowsiness, the relative direction of carbohydrate *v.* protein effects appears to be similar (Spring *et al.* 1983; Rosenthal *et al.* 1989): at noon, both protein- and carbohydrate-rich meals induce some drowsiness, but the effect is greater after carbohydrate. In the morning, any breakfast reduces fatigue in regular breakfast eaters; however, a

carbohydrate-rich breakfast tends to reduce fatigue less than a protein-rich breakfast.

5.4. Caffeine-driven activation

A large number of studies have looked at the psychoactive effects of caffeine on the central nervous system (for reviews, see James, 1991; Nehlig *et al.* 1992). In general, caffeine is regarded as a psychostimulant. It also leads to increased anxiety at higher doses in some susceptible individuals. In many regular consumers of caffeine, the cessation of caffeine consumption is followed by adverse changes, such as headache, drowsiness and fatigue (Silverman *et al.* 1992). Richardson *et al.* (1995) found two patterns of results after deprivation from caffeine. After overnight (13 h) deprivation, subjects showed significantly increased levels of tiredness and drowsiness, and more anger and dejection. The other pattern was less clear-cut. After caffeine deprivation for 13 h or 7 d, subjects tended to report poorer mood and more headache. Several studies have found that the symptoms of increased tiredness, drowsiness, anger, and dejection were present in subjects after overnight or 24 h deprivation, but not after longer deprivation periods. Thus, the recent use of caffeine determines to a large extent the present effects of caffeine (Rogers, 1995). This makes it difficult to determine whether the experimental results on effects of caffeine, often reported after an overnight caffeine deprivation, are due to beneficial effects of caffeine or to the amelioration of the negative consequences of short-term caffeine deprivation.

6. Influence of food and individual nutrients on affective state

6.1. Overview

Certain foods or individual nutrients have been implicated in behavioural distress involving mood shifts. One argument is that affected individuals self-medicate, using food or drink to combat aversive mood states characterized by frustration, anxiety, or depression. Alternatively, some individuals may refrain from eating certain foods in order to avoid their putative behavioural toxicity, according to the view that certain dietary constituents are aetiological agents for various forms of dysfunctional behaviour and negative affect (Christensen *et al.* 1989). For example, simple sugars have been variously blamed for disturbances in mood, sleep, and cognitive performance (Kruesi & Rapoport, 1986).

6.2. Diet-related dysphoria

One phenomenon that has received significant attention is the concomitant occurrence of dysphoria, a state of feeling unwell or unhappy, with a predilection for foods high in sugar or starch, so-called 'carbohydrate craving' (Wurtman, 1984; Lieberman *et al.* 1986). This is consistent with the observation that preferences for sweet and starchy foods increase during depressive episodes (Fernstrom *et al.* 1987) and with reports that carbohydrates can provide a temporary elevation in energy (Thayer, 1987) and mood (Lieberman *et al.* 1986). Certain clinical conditions, including premenstrual syndrome (Wurtman *et al.* 1989), bulimic episodes

(Rosenthal & Hefferman, 1986), seasonal affective disorder (Rosenthal *et al.* 1989), and atypical depression (Wallin & Rissanen, 1994), as well as withdrawal from alcohol, caffeine and tobacco over-consumption (Rosenthal *et al.* 1989), have similarly been linked to increases in carbohydrate intake. Patients describe themselves as anxious, tense, or depressed before a carbohydrate snack and peaceful and relaxed afterwards (Wurtman, 1984).

The paradox of this approach is that any improvement in mood accompanying carbohydrate snacks or meals, as with alcohol (Lloyd & Rogers, 1995) and probably drug use, is typically followed by a more prolonged period of increased anxiety, fatigue, and depression (Thayer, 1987; Milgram, 1990). The motivation to alleviate the negative mood state is high and, as such, it appears to be the initial positive effect and not the ensuing negative consequence that is remembered (Tamerin & Mendelson, 1969). This is consistent with recent work demonstrating that chocolate did not improve general mood state in a group of self-identified 'chocolate addicts'. The mood lift experienced was short-lived and the strategy self-defeating; eating chocolate ultimately led to feelings of guilt not detected in controls (Macdiarmid & Hetherington, 1995). It is presently held that sensory, rather than pharmacological, effects underlie the satisfaction experienced when a craving for chocolate is met (Michener & Rozin, 1994).

6.3. Central neurochemical activity and mood state

The proposed relationship between the composition of foods and their putative mood-altering effects has been linked to the serotonin hypothesis of Fernstrom and Wurtman (Fernstrom & Wurtman, 1972; Fernstrom, 1994) (see section 4.4.1.). Central serotonergic imbalance has been linked to disorders of food intake and affective behaviour. As to whether these are interrelated via dietary tryptophan insufficiency and so-called carbohydrate craving, the experimental support is mixed. Young *et al.* (1985) reported that tryptophan depletion in human subjects can lead to mild dysphoria, but Benkelfat *et al.* (1994) recently suggested that this occurs only in susceptible individuals such as subjects with a multi-generational history of major affective disorders. Early workers demonstrated that carbohydrate can ameliorate dysphoria (Lieberman *et al.* 1986; Wurtman *et al.* 1989); however, Reid & Hammersley (1995) recently failed to find any effect of carbohydrate ingestion on measured mood state immediately, 30 or 60 min after ingestion.

Studies have failed to find carbohydrate *v.* protein effects on mood, despite significant effects on the tryptophan : large neutral amino acid ratio (Deijen *et al.* 1989; Christensen & Redig, 1993). One problem is that the influence of dietary manipulations on the plasma tryptophan : large neutral amino acid ratio is probably too small to produce significant changes in brain serotoninergic function (Young, 1991). However, there is some evidence to suggest that diet can influence the tryptophan : large neutral amino acid ratio (Schweiger *et al.* 1986; Goodwin *et al.* 1987). The latter study also found significant correlations between carbohydrate ratio, amino acid ratio and mood.

Interest in 'carbohydrate cravers' as a clinical subpopulation may be waning. Schlundt *et al.* (1993) failed to find evidence that self-labelled cravers of sweet foods consume an abnormally high proportion of high-carbohydrate, low-protein foods, and Drewnowski (1990), noting that so-called carbohydrate cravers typically identify chocolate, ice-cream, and other desserts as their preferred foods, each of these deriving the highest proportion of their energy from fat, has questioned whether, in fact, such a clinical subgroup exists.

6.4. Other links between nutrition, mood and brain serotonin levels

Tryptophan deficiency has recently been linked to dysphoria-related alcohol abuse. Adams *et al.* (1995) have suggested that alcohol abuse may be a result of abnormal serotonergic activity in certain individuals, based on the hypothesis that alcohol can mimic the central effects of serotonin. Although purely speculative at this point, ethanol may merit further study with respect to its capacity to modulate central serotonin activity and ameliorate depressive episodes.

Certain vitamin deficiencies have also been implicated in psychiatric symptoms such as psychosis and depression. Pellagra, resulting from severe niacin deficiency, is the classic example (Lipton & Kane, 1983). Folate deficiency is characterized by deficient levels of its metabolic precursor, *S*-adenosylmethionine. In view of the possibility that the anti-depressant effects of *S*-adenosylmethionine may raise brain serotonin levels, folate deficiency has been implicated in serotonin-related depressive episodes (Young, 1993). In the absence of deficiency, however, there is no evidence that vitamin supplementation improves mood or is a potential treatment for behavioural problems (Kruesi & Rapoport, 1986).

Does carbohydrate intake improve mood state by normalizing central serotonergic activity or, as is the case with vitamin (or mineral) supplementation, is function (e.g. affective state) merely restored subsequent to a tryptophan imbalance or deficiency? The apparent co-morbidity of dysphoria and so-called carbohydrate craving requires further exploration in light of evidence that dietary tryptophan modulates affective behaviour. Special attention should be given to dose–response effects in well-characterized population subgroups and, in particular, to resolving the paradox between short- and long-term effects.

7. Nutrition and endorphins

A reciprocal relationship has been proposed to exist between the intake of various foods and the activation of endogenous opioid responses in the central nervous system. Matsumura *et al.* (1982) established that the oral ingestion of a light meal and the consequent stimulation of gastric function were associated with the increase in plasma β-endorphin levels in human subjects. This suggests that endorphins, endogenous opioid substances involved in pain perception and reward, could be increased in the post-meal period as a result of the normal processing of food in the digestive tract. Ingesting foods might therefore be a means of reducing pain perception and altering mood state.

At present, the literature remains confusing. Several experiments in isolated rat pups have shown that infusion of sugar into the mouth stops distress vocalizations, again suggesting a calming, rewarding effect of sucrose (Blass *et al.* 1987; Blass & Fitzgerald, 1988), while Dum *et al.* (1983) reported that a palatable food reward (chocolate milk) appeared to influence β-endorphin activity in rats, as judged by their behavioural response to administration of the opioid receptor antagonist naloxone. Hyperphagic obese rats are more tolerant to painful stimuli than controls, which suggests a higher level of opioid activity, perhaps due to overeating (Ramzan *et al.* 1993).

In rats with continuous access to a palatable sucrose solution, hypersensitivity rather than hyposensitivity to painful stimuli has been observed (Roane & Martin, 1990). Pain sensitivity in rats has also been shown to decrease after food deprivation (McGivern & Berntson, 1980). Melchior *et al.* (1991) found no increase in circulating β-endorphin levels in human subjects after the intake of a highly palatable meal, while high levels of β-endorphins have been found in patients with anorexia nervosa (Kaye *et al.* 1982). Women who consume palatable foods show increased pain tolerance, as measured using a pressure algometer, compared with those receiving unpalatable foods, neutral foods, or nothing (Mercer & Holder, 1997).

8. Safety issues

8.1. Overview

The safety of food additives and novel ingredients can only be assured after identifying limits of potential toxicity and, from these data, establishing acceptable daily intake levels. Populations with special dietary needs, e.g. the young, the elderly, and persons at risk of certain metabolic diseases, such as phenylketonuria, merit particular consideration. Whether the substance is used as a food additive or replacer, continued surveillance is necessary in order to identify potentially adverse or toxic effects, particularly with regard to cumulative intakes.

8.2. Tryptophan

An individual consuming about 100 g protein/d would ingest about 0·8 g tryptophan. A recent report on the safety of amino acids concluded that 3 g L-tryptophan/d can be taken without adverse effects (Anderson & Raiten, 1992), but there is not enough information to estimate a safe level of intake for D-tryptophan.

In 1989, a new disease characterized by blood eosinophilia (raised number of a type of leucocyte) and myalgia (severe muscle pain), termed eosinophilia–myalgia syndrome, caused a number of deaths. Those suffering from this illness had all apparently consumed L-tryptophan supplements before the onset of the syndrome. Further research showed that this disease was linked to the L-tryptophan manufactured by one single company, leading investigators ultimately to conclude that the lethal reaction was probably triggered by an impurity resulting from the manufacturing process and not by the L-tryptophan itself (Mayeno & Gleich, 1994).

8.3. Caffeine

The potential toxicity of caffeine has been thoroughly investigated by public health organizations. A typical cup of coffee contains between 70 and 140 mg caffeine. For a 70 kg person, this would amount to 1–2 mg caffeine/kg body weight, which would produce peak plasma levels of between 1 and 2 μg/ml. The effects of caffeine differ between habitual and non-users of caffeine and depend on the timing of caffeine intake, i.e. whether taken as a single dose or spread over the day. The evidence suggests that adverse effects and toxicity of caffeine are negligible, even in newborns, when plasma concentrations remain below 20 μg/ml. Thus, for adults, 250 mg/d (about 2·5 cups of coffee) should be a safe dose, which can be increased to 350 mg/d if only minor effects are considered. Acute toxicity begins when plasma concentrations reach 30–50 μg/ml (Stavric, 1988), and caffeine intake can be as high as 500 mg/d without any major side-effects (Debry, 1989). More research is needed to ascertain the long-term effects of habitual caffeine intake, in particular on hypertension and osteoporosis.

8.4. Macronutrient substitutes and flavour enhancers

The safety of the high-intensity sweeteners currently in the food supply has been a long-standing cause for public concern. However, these have been extensively evaluated and there is no substantive evidence that they pose a risk (Walker, 1995). As most fat substitutes are derived from non-synthetic materials such as starch gums, soluble fibre, and food proteins, these are generally recognized as safe. The important exception would be SPE which, after detailed reviews addressing concerns regarding digestibility and impaired absorption of fat-soluble vitamins, won approval by the US Food and Drug Administration for limited use in commercial food products (Lindley, 1993). Most flavour enhancers such as MSG are generally consumed in very small quantities on a daily basis. Glutamic acid is a substance of minimal toxicity and an acceptable daily intake level is currently 'not specified' (World Health Organization, 1987).

9. Hyperactivity

9.1. Overview

Hyperactivity or, more precisely, attention-deficit/hyperactivity disorder is a condition most often seen in children, and more often in boys than in girls (American Psychiatric Association, 1994). These children are often described by their mothers as 'overactive,' 'doesn't finish projects', 'fidgets', 'can't sit still at meals', 'doesn't stay with games', or 'talks too much' (Stewart, 1970). There are two popular hypotheses about the aetiology of hyperactivity, one relating hyperactivity to the consumption of sugar, the other to food additives.

9.2. Hyperactivity and sugar

Crook (1974) observed that when sucrose was eliminated from a hyperactive child's diet, behaviour improved, but the symptoms returned when sugar was reintroduced. Similarly,

Rapp (1978) eliminated various food items including sucrose from the diet of hyperactive children. In seven out of twenty-one cases, the parents reported that hyperactive behaviour increased as sugar was reinstated. Based on these and other case studies, sugar was concluded to be a major cause of hyperactivity. However, these studies have methodological problems. Removing sugar from a diet will change many aspects of the diet. The omission of control groups or the lack of a double-blind intervention makes it possible that expectations and suggestions, rather than sugar, are responsible for the behavioural changes.

Several correlational studies have also supported the idea that sugar plays a role in hyperactivity. Prinz *et al.* (1980) compared twenty-six hyperactive children with twenty-six controls for 'destructive–aggressive' behaviours and restlessness. In the hyperactive group they found a correlation between sugar intake (as estimated from a food diary of the previous week) and destructive–aggressive behaviours. A correlation between sugar intake and activity was also observed in the children in the control group. Wolraich *et al.* (1986) failed to find significant correlations between behaviour and sugar intake, although there was some evidence that a higher sugar : total energy ratio was associated with elevated activity, off-task behaviours and attention-shifts. When comparing pre-school boys who consumed the largest amounts of sugar with boys who consumed the least amounts in a vigilance test, Prinz & Riddle (1986) found that the high sugar group was less able to sustain attention.

The majority of experimental studies do not support the idea that sugar consumption leads to an increase in activity or hyperactivity. A number of studies comparing a sucrose challenge with a placebo, usually saccharin or aspartame, did not find differences in diverse measures like activity (assessed by an actometer or by the Conners rating scale), impulsivity, or locomotion (Wolraich *et al.* 1985; Ferguson *et al.* 1986; Roshon & Hagen, 1989). Behavioural differences following sugar *v.* placebo were not found even when children diagnosed with attention deficit disorder were investigated (Mahan *et al.* 1988; Wender & Solanto, 1991), and some studies even found a decrease in activity levels after consumption of sucrose or glucose (Behar *et al.* 1984; Saravis *et al.* 1990). Even though a few studies report higher activity in children after high doses of sucrose (e.g. Rosen *et al.* 1988), the experimental evidence, taken altogether, does not support a causal association between sugar and activity. A reverse causality can also be envisaged: hyperactive children need more energy, and more sugar, than sedentary peers.

9.3. Hyperactivity and food additives

Feingold (1981) proposed that hyperactivity is due to an increased tendency of children to react to food additives such as artificial flavours, artificial colours, and preservatives. He eliminated these substances from a dietary regimen that came to be known as 'the Feingold diet'. Some support for the Feingold diet comes from an experiment with twenty hyperactive and twenty non-hyperactive children (Swanson & Kinsbourne, 1980). All children were put on the Feingold diet for 5 d. They received a capsule with

either placebo or food dyes on days 4 and 5 and learning tasks were conducted on these days. The hyperactive, but not the non-hyperactive, children performed worse on this task after receiving food dyes as compared with placebo. However, as a relatively high dose of food dyes was used, this study design is not appropriate if the effects of food dyes in a normal diet are to be evaluated. In addition, it is not clear whether the experiment was conducted double-blind or not (Logue, 1991). In an experimental study of twenty-two hyperactive children who were on the Feingold diet for a number of months, Weiss et al. (1980) gave average doses of food dyes on some days in a double-blind trial. In only two of the twenty-two children were the mothers able to detect effects of the dyes. In the other twenty, food dyes had no discernible effect. There is, to date, insufficient scientific evidence to support the Feingold hypothesis (Kolata, 1982; Logue, 1991).

10. Critical assessment of the science base: identification of criteria

The preceding survey of the scientific literature supports the view that, under certain circumstances, certain foods or food constituents can influence the cognitive and affective processes that drive human behaviour. Establishing a link between diet and behaviour is uniquely complex because the impetus for this sort of research often comes from outside the scientific community. To complicate matters, the news media typically jump in as *de facto* reviewers, overstating the importance of the latest findings, leaving the general public confused and frustrated when conflicting evidence subsequently appears.

Research exploring the putative link between diet and behaviour and/or related cognitive or emotional functioning (e.g. appetite and satiety, mood, cognition, performance, or pain perception) must conform to the rigorous scientific principles designed to guide researchers in the area of human behaviour as stringently as in any other scientific field. The following criteria should be kept in mind.

(1) Hypotheses must be based on validated, scientifically-established knowledge. Accordingly, a set of quantifiable independent and dependent variables must be integrated in research protocols designed to elucidate causal relationships.

(2) In interventional studies concerning food intake behaviour, statistically valid prospective data are required to confirm claims that certain foods or food constituents exert a stronger influence on appetite and satiety than could be expected on the basis of energy or nutrient content. This must be translated into measurable alterations in long-term intake and consequent effects on body weight.

(3) Laboratory studies must quantitatively demonstrate motivational effects on appetite and satiety. As artificial constraints are typically imposed, caution must be applied in generalizing results to naturalistic conditions. Studies of food intake motivation should clearly delineate the test conditions; that is, subject characteristics such as sex, age, BMI, and cognitive set, as well as other independent variables concerning the nature,

amount, time course of ingestive events, and the ethnic, social, emotional, and physiological context of the experiment. Ideally, short-term laboratory studies will inspire hypotheses regarding long-term effects, which may then be tested in large field studies. Dose–response and temporal relationships are critical and should be specifically investigated.

(4) Whenever cognition, mood, or other aspects of performance are tested, validated *ad hoc* tests should be used in order to measure dependent effects, with special attention given to classic tests translated into foreign languages (and validated before they are used).

(5) The large variability seen in all aspects of human behaviour makes the establishment of clear treatment effects highly challenging. Nevertheless, no leniency should be tolerated in the use of stringent statistical significance criteria, which should be established from the outset.

(6) There should be clear evidence that agents designed to modify behaviour or psychological functions are safe, and this must apply to all potential user groups, particularly those over-consumers exposing themselves to the highest level of risk. Ingredients designed to modify diet composition must be demonstrated to produce favourable effects exclusively, with potential changes in food choices and the resulting nutrient content of habitual diet corresponding to nutritional recommendations. Constituents that modify appetite or satiety should not contribute to deterioration of nutritional balance. Potential maximum intake from dietary sources should be estimated.

(7) Four important caveats regarding data interpretation should be kept in mind: (a) data derived from animal models cannot replace human studies; (b) short-term response patterns do not necessarily reflect what will happen over the long term; a phenomenon happening over a few minutes or hours, no matter how impressive, should not be assumed to affect long-term motivation or behaviour; (c) results obtained from studies covering one type of subject or group should not be generalized *a priori* to the general population; (d) functionality needs to be viewed in the context of food safety; the difference between dietary and pharmacological effects must be acknowledged.

(8) Whenever possible, biomarkers of nutritional manipulations should be investigated. Although a cause–effect relationship can be demonstrated at the behavioural level, the biological mechanisms responsible for the observed phenomena are worth elucidating since they allow a deeper understanding of the critical elements governing behaviour.

11. Considerations for future research

11.1. Appetite and satiety

With respect to macronutrient-specific appetite and macronutrient-specific satiety, additional research is needed to separate the effects of macronutrient composition of foods from effects related to their sensory characteristics (Johnson & Vickers, 1993; Lloyd et al. 1994). The effects of

food consumption can be compared by adjusting macro-nutrient composition while leaving sensory characteristics unchanged, and by comparing foods with the same macro-nutrient composition but different sensory characteristics. Modelling, with respect to estimation of macronutrient-specific compensation (see Beaton *et al.* 1992) might also be refined. It would be of interest to explore whether parameters representing macronutrient-specific satiety and sensory-specific satiety could be included in this model. Estimation of energy balance and body weight (Westerterp *et al.* 1995) has also been very useful. It might be possible to refine this model to take nutrient (as well as energy) balance into account. In this way, specific effects of macronutrients on energy intake and on body-weight regulation might be predicted.

11.2. Macronutrient replacers

With nutrient composition on commercial food labels increasingly common, consumers are generally familiar with the energy and macronutrient contents of the foods they choose. Future work needs to include food intake manipulations in subjects that are aware of the composition of the test foods they are served. Since responses can depend on whether the foods are given in solid or liquid form (Tournier & Louis-Sylvestre, 1991), where possible test meals should be whole, conventional foods that people might normally consume. In addition, subjects' underlying motivation (e.g. passive avoidance of dietary energy, active dieting) *vis-à-vis* consumption of low-sugar and low-fat foods should also be taken into account (Blundell & Green, 1996).

The effects of chronic use of energy-reduced foods on body weight, body composition, nutritional balance are only partially predictable on the basis of present knowledge. The variation typical of day-to-day ingestive behaviour confounds interpretation of short-term studies. Current understanding of the temporal pattern or time frame of energy and macronutrient compensation also remains incomplete. Further studies involving extended-time subject observation (weeks, months or years) are needed before the functional claims made for low-energy substitutes for fats and sugars can be adequately assessed.

11.3. Palatability enhancers

One question that remains unanswered is how MSG may influence long-term control of body weight and nutritional status. Objective measures of intake behaviour must be made over long periods of time, which again raises the issues of long-term control of food stimulation and monitoring of intake in free-living persons. Corollary effects on vitality, immune function, and other indices of general health in at-risk populations are also important issues that remain unexplored.

11.4. Cognitive performance

Many of the effects regarding performance on complex tasks and cognitive load are subject to modulating factors. These include time of day (diurnal rhythm), personality type (extroversion–introversion), level of arousal, load or difficulty of the task, and the nature of the task itself.

Future prospects for research on diet and cognitive performance should address several important issues including complex cognitive performance, the nature of the tasks and task load used, identification of subgroups susceptible to the effects of nutritional manipulations, interactions between subjective and objective measures of performance and the necessary methodological complexity required to assess these effects.

Cognitive performance can be affected by specific nutritional manipulations. However, the tests used have typically considered single components of cognitive function. The way in which these aspects of performance relate to compound tasks which require simultaneous use of multiple faculties, such as driving or operating machinery, is not clear. It is therefore important to demonstrate whether nutritional manipulations exert a net effect on complex cognitive performance in total or on specific aspects of a task with no detriment to the whole task.

11.5. Pain perception

More research is needed before the relationship between pain perception and food ingestion is elucidated. Of particular importance are the measurements of central as well as peripheral levels of opioids, the comparison of short- *v.* long-term effects, and comparative observations of normal-weight *v.* obese individuals.

11.6. Sensitive subgroups

Specific subgroups of people may demonstrate sensitivity to nutritional interventions or have particular needs. Sensitivity has been shown in the young and the elderly, particularly when concomitant dietary deficiencies are present. Other research has identified dieters as a group that demonstrate decrements in certain aspects of performance (Green & Rogers, 1995). A further subgroup likely to be susceptible to nutritional manipulations is those individuals operating under stressful challenges (e.g. long-distance truck drivers).

11.7. Time-dependent effects

A certain degree of methodological complexity is required to critically assess nutritional effects. One requirement is to control for effects and interactions with circadian rhythms. For example, carbohydrate may have different effects when presented at different times of day. Potential biphasic effects, whereby an intervention produces an initial positive effect on performance and a subsequent negative effect, may occur following the administration of certain substances, e.g. glucose or caffeine. However, biphasic effects *vis-à-vis* other manipulations have not been examined.

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