Diet, behaviour and cognitive functions: a psychobiological view

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Abstract

There is a rapidly growing interest in the scientific study of the effects of foods on psychological processes involved in the control of behaviour (performance) and cognitive functions such as memory, perception, attention and vigilance. This study forms part of innovative research on functional foods, which provides an active arena for collaboration between researchers in universities, institutes and industry. Research outputs will inform legislation currently being drawn up in Europe. This article describes some basic issues of functional food research exemplified by evidence on the effects of carbohydrate foods. These effects implicate glucose metabolism in some aspects of human memory and performance. One specific issue concerns the problem of daytime lethargy and the "post-lunch dip". An exciting prospect for this type of work is the potential to develop foods to maintain or improve performance in the working environment and to enhance quality of life.

Keywords: *blood glucose*; *memory*; *post-lunch dip*; *cognitive performance*; *carbohydrates*

Background

Traditionally, Eastern medicine has used foods and other edible materials to evoke changes in behaviour, mood and thought processes. Examples are traditional Chinese medicine (TCM) and foods for specified health use (FOSHU) in Japan, and these represent the interface between Eastern and Western ideologies regarding food–health interrelationships. The concept of functional foods (or nutraceuticals) embodies these ideas. Its study has been a foreground for the active interaction between scientific, political and industrial domains. Recently, these ideas have inspired an Institute of Life Sciences (ILSI)–European Union (EU) project termed Functional Food Science in Europe (FUFOSE) (1). Another collaborative project, involving European food industries and academic researchers, is currently examining the status of food claims. This project, named Process for the Assessment of the Scientific Support for Claims on Foods (PASSCLAIM), regards scientific evidence as instrumental in separating truth from hyperbole. Importantly, the FUFOSE and PASSCLAIM projects have identified two types of claims, termed A and B. The type A claim involves a statement about "enhanced function" (e.g. a given food improves

concentration), whereas a type B claim refers to a "reduction in disease" (e.g. a certain food prevents heart disease).

Investigations into the effects of foods often involve the identification of intermediate markers, sometimes called biomarkers, in the causal processes linking food ingestion with an endpoint. The conceptual scheme that underlies the VINNOVA project has been designed to investigate the functional properties of certain types of food. Fig. 1 shows how the metabolic effects of foods can be related to their effects on satiety (appetite control), cognitive performance and mood. This novel programme has been designed to map the effects of foods on satiety and performance, while simultaneously seeking to identify biomarkers for both phenomena.

The more remarkable claims about foods typically refer to their effects on mental capacities, which are known as cognitive functions or cognitions, and this area is of considerable research interest. Cognitive functions are mental activities that allow organisms, including humans, to perceive, understand and act upon the environment, thereby optimizing adaptation and performance. The development of cognitive abilities through evolution has
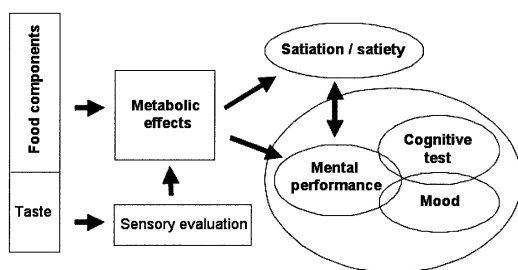
Fig. 1. Effects of food components on satiation, satiety and mental performance and their metabolic correlates.

permitted certain species to master their environment. Brain processes that provide accurate perception and memory of environmental events enable organisms to function successfully. Given their critical importance in human functioning, cognitions are usually operating at a high level, and may be protected from degradation by applying extra effort. Consequently, demonstrating the effect of dietary (or other) interventions on performance is typically difficult.

In humans, cognitive abilities are fundamental in everyday tasks, such as driving, operating machinery and academic work. These complex skills are composed of a number of individual cognitive processes, such as attention to, and perception of, the environment, the acquisition, storage, organization and retrieval of information, and the organization of effective response patterns. These processes (commonly known as concentrating, thinking, remembering and acting) direct the design of laboratory-based tests of individual cognitive functions. The validity and sensitivity of these tests are crucial to any methodology professing to assess the effects of foods and food components on cognitive functioning.

This article describes the effects of carbohydrates (CHO) on cognitions and moods, as mediated via changes in the availability of blood glucose. Furthermore, it discusses the relevance of this work to the "post-lunch dip" (PLD). Finally, it articulates the factors that are important in designing studies that aim to explore the effects of glucose on cognition.

Glucose as neural fuel

Glucose is the only metabolic fuel available to the brain. It is required for the synthesis of neurotransmitters such as serotonin (5-hydroxytryptamine, 5-HT), noradrenaline (NA) and acetylcholine (ACh). Other mechanisms influence cognition, e.g. 5-HT

availability, which in turn may be influenced by CHO/protein intake, by altering the ratio of tryptophan:large neutral amino acids.

Effects of glucose on cognition and mood

The normal level of blood glucose is 4–5.5 mmol l^{-1}. This is controlled by a series of hormonal mechanisms. When it falls below 2.2 mmol l^{-1}, hypoglycaemia occurs. The decline in glucose, occurring in both mild and severe hypoglycaemia, impairs performance (2). Subjective effects of neuroglycopenia (low blood glucose at the neuronal level) include negative mood (e.g. increased tension and anger) and attenuated arousal (e.g. drowsiness).

Numerous reports suggest that memory is particularly affected by changes in glucose availability. Verbal memory and concept formation, in particular, are the most commonly affected cognitive functions in type II diabetes (2). However, these functions are not impaired in experimentally induced hypoglycaemia. A series of studies in elderly subjects showed that glucose enhanced (short-term) working memory (3).

Glucose administration has reportedly been shown to benefit memory in young adults and the elderly (4). In one study, the performance of subjects who had consumed breakfast, and those who had not, was compared on three memory tasks (5). The "no breakfast" condition was associated with poorer recall, but this effect was reversed by the administration of a glucose drink at breakfast time, in two of the three memory tasks.

The effects of glucose on cognition are summarized in Table 1.

Recovery from nadir and rising levels of blood glucose were associated with better recall than were falling blood glucose levels (18, 19). The effect of 50 g glucose on memory for trigrams depends on the initial blood glucose levels of the subject (8) (Fig. 2). Those with higher levels of blood glucose showed better performance. However, after the glucose drink, falling levels of blood glucose were associated with better memory performance. The decline in blood glucose during task performance is thought to indicate that increased neural uptake of glucose results in better memory.

One study found that a high CHO drink enhanced the number of words correctly recalled, compared with a low CHO drink (9). Moreover, a change in blood glucose was a significant covariate in the high CHO condition, but not in the low CHO

Table 1. Effects of glucose on cognition

Reference	Sample	Study design	Cognitive testing	Results	Comments
Deijen et al. (6)	21 cadets (2 groups of 10 and 11 receiving 2 different drinks)	5 daily doses of an isocaloric drink (255 kcal): protein-rich drink (2 g tyrosine); CHO-rich drink	Memory task. Assessment before the combat course and on the 6th day of the course	Group with the tyrosine-rich drink performed better on a memory task than the group consuming the CHO-rich drink	Between-subjects design
Benton et al. (7)	70 young F students	Glucose drink (50 g) after baseline and 25 g 25 min later or CHO-free placebo drinks (sweetened with aspartame and acesulfame K)	Memory task	Improved recall after glucose drink. No differential effect on primacy or recency	Between subjects. No dietary restrictions on test day
Martin and Benton (8)	80 F students	4 groups: breakfast and 50 g glucose drink ($n = 28$); breakfast and placebo drink ($n = 25$); fasted and 50 g glucose drink ($n = 12$); fasted and placebo drink ($n = 15$)	Brown–Petersen memory task	Poorer performance after fasting. Glucose improved memory in fasted subjects. Breakfast consumption associated with better memory. Rapidly falling blood glucose associated with better memory	Between subjects. Nature of breakfast consumed not known/controlled
Metzger (9)	23 young F and 11 M students	2 groups: 50 g glucose in drink (5M, 12F); 23.7 mg saccharin in drink (6M, 11F)	Facial recognition task	No difference in target identification between saccharin/glucose consumption before test. Fewer false positives and enhanced signal detection after glucose drink	Between subjects. Restrained from eating or drinking anything but water for 9 h before test
Green et al. (10)	26 young M and F students	4 groups: glucose drink (× 2); aspartame (placebo) drink (× 2)	Two-finger tapping task. Adaptation of Sternberg recognition memory task (1966). Verbal free recall task. Bakan task	Glucose enhanced recognition memory times. Enhanced Bakan performance compared with control	Within subjects. Abstinence from food/glucose or sucrose-containing drinks and strenuous exercise for 8 h
Foster et al. (11)	30 young F students	3 groups: 25 g glucose drink after baseline; 37.5 mg saccharin drink (placebo); 300 ml water (placebo)	Memory: immediate, short delay and long-term long delay; long-term non-verbal (Rey–Osterrieth complex figure drawing, 1944); working memory span (Wechsler, 1981, 1984)	Glucose facilitation of long-term verbal free and cued recall. No effect on short-term verbal memory or long-term non-verbal memory	Between subjects
Kelly et al. (12)	Experiment 1: 2 groups of 6 subjects	4 lunches varying in energy and fat and CHO content: LF/low energy (431 kcal); HF/high energy (844 kcal); LCHO/low energy (432 kcal); HCHO/high energy (840 kcal)	Number recognition task; repeated acquisition task. Assessment before and after consuming lunch (experiment 1); after breakfast and lunch (experiment 2)	In both experiments: performance on the tasks was poorer after than before the meal; there were no systematic variations in performance as a consequence of either the energy or macronutrient content of the meals	Limited number of subjects and dimension measured. Subjects allowed to choose among the tasks. Unrestricted access to caffeine and nicotine
	Experiment 2: 2 groups of 6 subjects	Breakfast, lunch and afternoon snack different in energy, fat and CHO content: LF (739 kcal); MF (1233 kcal); HF (1685 kcal); LCHO (703 kcal); MCHO (1213 kcal); HCHO (1666 kcal)			
Lloyd et al. (13)	18 subjects (3M, 15F), mean age 27 years	3 isocaloric lunches (about 700 kcal): LF/HCHO (694 kcal, 29/54% energy); MF/MCHO (706 kcal, 45/42% energy); HF/LCHO (720 kcal, 62/24% energy)	Free recall task (memory). Assessment 30 min before lunch, 30, 90 and 150 min after finishing lunch	No effect on memory	
Lluch et al. (14)	32 volunteers (16M, 16F); 17 LF and 15 HF consumers	2 isocaloric breakfast (410 kcal) and lunches (740 kcal for F, 990 kcal for M); LF/HCHO (breakfast: 22/67% energy; lunch: 20/61% energy); HF/LCHO (breakfast: 48/42% energy, lunch: 54/32% energy)	Associative memory (code substitution). Assessment just before and 30 min after finishing lunch	No effect on memory task. No effect of habitual diet on performance	
Kanarek and Swinney (15)	Experiment 1: 16M (19–22 years)	4 conditions: breakfast (300 kcal) followed by: lunch + caloric snack (confectionery snack); no lunch + caloric snack; lunch + non-caloric snack (drink); no lunch + non-caloric snack (drink)	Digit span recall (forwards and backwards). Assessment 15 min after eating snack	Subjects recalled more digits in the backward digit span test after the caloric snack than after the non-caloric snack	Practice effects observed. Pre-lunch performance not assessed (in both experiments)
Parker and Benton (16)	33 university students (17M, 16F), mean age 21 years	2 conditions: no breakfast; milk-based nutritional beverage	Spatial memory. Immediate recall. Assessment 2 h after breakfast	Subjects who ate a breakfast took less time to finish memory tasks than subjects who did not have breakfast. No effect on number of errors	Between subjects
Smith et al. (17)	48 university students (24M, 24F)	4 conditions: 3 course meal (1200–1500 kcal) + decaffeinated drink; 3 course meal (1200–1500 kcal) + caffeinated drink; no meal + decaffeinated drink; no meal + caffeinated drink	Free recall task. Delayed recognition memory task. Assessment before the meal and 90 and 180 min after the start of the meal	No effects on memory tasks	Effects were different to those observed after lunch or breakfast

M: male; F: female; LF: low fat; HF: high fat; MF: medium fat; CHO: carbohydrates; LCHO: low carbohydrate; HCHO: high carbohydrate; MCHO: medium carbohydrate.
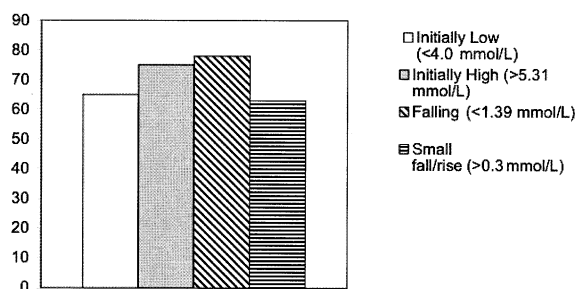
Fig. 2. Percentage of trigrams recalled as a function of blood glucose and change in blood glucose during the task. (Adapted from Martin & Benton, 1999).

condition for both the critical flicker fusion threshold (CFFT) and memory performance. Poorer performance may be due to a lack of available energy, and consequently lower blood glucose.

Reaction time tasks appear to be sensitive to changes in blood glucose. Following a glucose drink, blood glucose level correlated with improved decision time (18). Poorer performance was associated with slower removal of glucose from the blood. However, glucose administration leaves unaltered the performance on digit span, tests of attention and motor function (3).

Test difficulty influences the apparent effects of glucose on cognition. More difficult tests produce a high cognitive demand. Thus, glucose reportedly enhances memory and some aspects of attention in normal adults, if tests are cognitively demanding. Cognitive demand increases glucose uptake (20). In one study, 25 g glucose was administered and memory performance was tested after either serial sevens (a highly demanding task) or a control task (20). Both tasks were followed by word retrieval (verbal fluency). Glucose consumption improved performance on serial sevens and verbal fluency. Peripheral measures of blood glucose decreased under the high cognitive load. This suggests that intense cognitive processing leads to increased neural glucose utilization. In addition, evidence from positron emission tomography (PET) suggests that increased neural activity (e.g. learning a complex visuospatial motor task or verbal working memory) is associated with an increased use of glucose by the brain (21). That frontal lobe functioning is enhanced by glucose suggests an increased supply of glucose to brain areas involved in memory tasks (20, 21). Alternatively (or additionally), glucose may activate the release of ACh during learning, to enhance memory performance.

Effects of carbohydrates at lunchtime

No studies examining the effects of CHO at lunchtime have described the glycaemic index (GI) of the dietary manipulation. Manipulations of the proportions of CHO and fat in lunchtime meals have produced diverse outcomes; some have shown CHO to produce a better effect on performance than fat, while others have shown the converse (13, 14, 22, 23). Higher than usual proportions of fat or CHO may induce drowsiness or uncertainty, or potentially affect cognitive efficiency and motor performance (24).

Two studies (23, 25) compared the performance effects of high-CHO and high-protein meals. One found no effect of either meal on auditory reaction time, irrespective of whether the meal was given at breakfast or lunch (23). The other, in contrast, found that auditory reaction time was slower following the CHO lunch (25). The nature of the CHO and the timing of ingestion may be important in explaining the different effects in each study.

Performance and the glycaemic index of foods

Fischer et al. (26) used test meals (400 kcal) of either pure CHO (glucose, maltodextrin and rice starch), protein or fat (a combination of saturated and unsaturated fatty acids). Protein ingestion resulted in better attention and efficiency on tasks, which was concomitant with higher metabolic activation. There were different effects of CHO and protein in peripheral versus central tasks. Thus, CHO resulted in relatively low peripheral performance and better central performance, while the opposite pattern was observed following protein ingestion. Fat had no effect on reaction time. The authors attributed this to the steady plasma concentrations of glucose, insulin and glucagon, as produced by fat consumption. Moreover, they observed that the ingestion of pure CHO induced slower reaction time, while pure protein produced faster reaction times on demanding complex (but not simple) reaction-time tasks. This effect was only apparent 2 h after ingestion, reflecting differences in the absorption and metabolism of the two macronutrients. The first hour following ingestion saw the reverse pattern.

Glucose tolerance

Glucose tolerance (i.e. the ability to take up glucose from the bloodstream to tissues) is posited as important in mediating nutritional effects on cognitive function. There are substantial individual

differences in glucose tolerance (27), as reflected in the susceptibility to impairment of cognitive performance. Subjects with higher levels of blood glucose and good glucose tolerance respond most efficiently to the demand of cognitive tasks (19). The threshold for impairment of cognitive tasks has been found to be within a range of 2.2–2.8 mmol l^{-1} (28). However, some individuals maintained normal performance at below 2.2 mmol l^{-1}, while others showed disruption of function at 4 mmol l^{-1}. It has been suggested that cognitive disruption at higher glucose levels occurs in non-diabetics, whose hypoglycaemic symptoms are relieved by food intake (19). Glucose tolerance can be improved by exercise and frequent, small meals, but effects on cognitive performance remain unknown. The response to hypoglycaemia is greater in males. Cognitive impairment is associated with impaired glucose tolerance and hyperinsulinaemia in non-diabetic samples of elderly persons (29). Some studies suggest that stable performance is related to balanced glucose metabolism and state of metabolic activation (26). This may be mediated via an action of glucose on the cholinergic system (30).

The post-lunch dip

The consensus view is that daytime sleepiness, or the afternoon decline in mental alertness (the PLD), is a circadian rhythm. This phenomenon has sparked considerable research interest in many European countries, given its association with a loss of work efficiency.

A review of six studies examining circadian rhythms in mental performance (31) deficits (particularly those related to attention) in the early afternoon was reported. Increasing meal size at lunchtime produces more momentary lapses of attention. This PLD effect is abolished by caffeine (32). Performance on sustained attention tasks is impaired in the early afternoon, compared with the late morning, irrespective of food consumption (22). It is seemingly difficult to disentangle the effects of lunch consumption from the rhythmic effects underlying the PLD. Declines could simply reflect the effect of a negative energy balance or a lack of available glucose.

Circadian patterns in mood may interact with food intake. Glucose and cortisol secretion (as responses to food intake) varies across the day. For example, alertness peaks in mid-morning, then falls throughout the day (33). The natural rhythm of cortisol exhibits diurnal variation. These rhythms may explain the different effects of meals on mood and performance across the day. Thus, the effects of alertness-enhancing foods are most likely to be detected if they are ingested at a time when alertness is naturally declining, and cognitive capacity is challenged by an appropriate cognitive test. For instance, the beneficial effects of afternoon snacks do not occur if snacks are given in the late morning (15). Therefore, task selection in the design of a test battery should embrace these considerations. Furthermore, physiological measures, e.g. blood glucose, insulin and fatty acids, are important biomarkers of the metabolic state of the individual following food consumption.

Dietary interventions that potentially modulate the PLD are of research interest. Varying the GI offers a considerable opportunity for functional food development, with potentially positive effects on the extent and timing of post-lunch inefficiency. Maintaining blood glucose appears to be beneficial. This can inform advice about breakfast consumption, snacking and the development of functional foods, which modulate blood glucose. The effect of CHO at lunchtime is therefore an important consideration.

Methodological considerations

Cognitive demand reportedly increases the uptake of glucose. The order of tests in a battery therefore warrants careful consideration and piloting with respect to the proposed intervention. A lack of effect may occur because the most demanding task is placed in a particular order in the battery (e.g. first or at the peak of a nutrient effect), when resources are most plentiful. Thus, the timing of tests after consumption and the relative order of tests within a battery must be considered in conjunction with data about the GI of the food, details of its likely course of digestion, and metabolism. Measurements of blood glucose immediately after cognitive testing may reflect arousal or stress produced by the cognitive tests (perhaps exacerbated by evaluation or apprehension of the participants), rather than an exclusive response to a nutrient intervention.

Conclusion

This article has summarized some of the evidence linking dietary interventions (mainly CHO) and cognitive performance. Dietary adjustments of glu-

cose availability influence performance, but the situation is not simple. Salient effects are seen in studies using large glucose loads. The effects of foods, however, are less precise. Individual differences in responses to foods and in glucose profiles are marked, and important in explaining the effects of interventions on cognitive performance and subjective state. These factors mitigate against the demonstration of clear effects on cognition. Moreover, given that cognitive function is strongly protected against disruption, innovative and carefully designed studies are imperative in demonstrating the subtle effects of food manipulations, and in examining the potential for the development of functional foods.

Acknowledgements

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