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Effects of food energy on cognitive performance: no support from event-related potentials (yet?)

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Several reviews of behavioural studies have concluded that some foods may have beneficial effects on cognitive performance. The present review summarises findings from studies using event-related potentials to investigate the food effects on brain activity underlying cognition. Despite initial positive indications from observational studies, subsequent studies with a within-subject design have not consistently confirmed these effects. This could be due to several factors, e.g. the use of attention tests (in contrast to memory tests employed in behavioural studies) and the lack of a control condition in some instances. Future studies could benefit from measuring cognitive performance with more difficult tests that tap into cognitive domains other than attention, using an appropriately controlled cross-over design, and a more systematic variation and complete description and characterisation of the food intervention.

Food energy: Cognitive performance: Event-related potentials: Attention

Glucose is the primary source of energy for the brain. As the capacity of the brain to store energy is limited[1], several studies have investigated the acute effects of food energy, particularly carbohydrates, on cognitive performance. Most of these studies have looked at the effects of a glucose-containing drink on memory and attention as assessed with behavioural tests[2–4]. Although the results of these studies are inconsistent, the main conclusion is that cognitive performance is impaired when energy is compromised (e.g. during hypoglycaemia), and that in energy-replete individuals dietary carbohydrates can indeed influence cognitive performance and verbal memory in particular[5].

The traditional and intuitively appealing hypothesis that ingested glucose improves cognition by directly increasing the uptake of glucose to the brain has frequently been questioned, and it is commonly acknowledged that this relationship is more complex than originally thought[6,7]. Psychophysiological measures can serve as a useful tool to help unravel this complex relationship. Indeed, parallel to behavioural research, the effects of food on cognitive performance have been investigated at the psychophysiological level using various methodologies, including event-related potentials (ERP).

ERP are a measure of electrical brain activity directly related to perception and cognitive processing of a particular event (i.e. a stimulus and/or a task). They are usually recorded in an experimental situation where the participant is asked to perform a computer-based cognitive task (e.g. a memory or attention task involving visual or auditory stimuli to memorise or focus upon). The subcomponents of ERP allow distinction of cognitive processes that are involved in the performance of the task at hand based on their correspondence with other measures of cognitive performance in carefully controlled behavioural and fMRI studies[8,9]. For example, the amplitude of the P3 wave during an attention task (a positive wave at 300 ms after presentation of an attended stimulus) represents the updating of the mental representation of stimuli[10]. The latency of the P3 (the time between the appearance of the attended stimulus and the P3 peak) is considered a measure of stimulus classification speed. Larger P3 amplitudes and shorter P3 latencies are seen as indicative of greater cognitive efficiency. For instance, several ERP studies have demonstrated that caffeine, which is generally known to improve attention measured behaviourally, increases P3 amplitude and decreases P3 latency (see Lorist & Tops[11] for a review).

The aim of the present review is to evaluate the evidence for acute effects of food energy on cognitive performance using event-related potentials as a measure of brain function. A literature search was performed using 'food', 'carbohydrate*', 'event-related potential*' and 'ERP*' as key words in PubMed. Relevant studies cited in the papers found via PubMed were also taken into account. Studies were included if the type and timing of food conditions were described, and the study included ERP measures related to cognitive performance. Food effects on early ERP components, such as P1, N1, P2 and N2, which are related to perception (i.e. sensory processing and basic encoding of information) rather than cognitive processes, such as memory and attention, are not considered in the present review.

Abbreviation: ERP, event-related potentials.

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Event-related potential studies on the cognitive effects of carbohydrates

Three initial observational studies using ERP as a measure of cognitive performance explored the relationship between self-determined food intake and selective attention (Table 1). In these early studies, the effects of food on attention were assessed in large groups of students using an auditory 'oddball' paradigm, where the task was to listen to a series of similar tones and to indicate when a different tone, which was presented infrequently, was heard. Food intake on the test day was assessed retrospectively using a questionnaire, and subgroups were defined *post hoc*. The first exploratory study found a positive relationship between food intake and amplitude of the P3, indicating better attention after a greater self-reported number of snacks and/or meals[12]. The two subsequent studies had smaller sample sizes and observed the relationship between attention and reported timing of the last meal before the attention test (<3 h *v.* >6 h before the test) and could only demonstrate a marginal correlation[13,14]. Due to the observational nature of these studies, it is unclear what the contribution of circadian effects and food composition to the reported effects on cognition was.

Subsequent studies continued using the auditory oddball paradigm and in addition controlled food intake experimentally (Table 2). In the second experiment described in Geisler & Polich[14], a lunch consisting of sandwiches, an apple and a fruit drink seemed to improve attention as indicated by a P3 amplitude larger than that before the meal. The fact that the increase in P3 amplitude already appeared immediately after the lunch, when digestion of foods could not have been complete, suggests that these attention effects may have been related to satiety rather than food energy. This possibly pertains to the peripheral secretion of peptide hormones such as insulin and ghrelin, which – besides regulating food intake and appetite – are also active in the brain areas involved in cognition[15]. In another study, attention became worse after a similar meal as evidenced by a marginally smaller P3 amplitude and a longer P3 latency[16]. The difference between these two studies can possibly be explained by the fact that the meals were served at a different time of day (at 09.00 and 11.00 hours, respectively). A caveat of both studies was that no control condition was employed. Thus, it could not be excluded that the differences in P3 amplitude were due to (an interaction between food and) circadian variation.

In three studies, circadian effects were controlled by measuring the same participants in a control and intervention condition at the same time of day. Geisler & Polich[17] compared the effects of a cola-flavoured beverage with glucose (no caffeine) to those of water on a visual attention task. No differences in P3 amplitude or latency were found up to 80 min after the intervention, despite the non-blinded character of the study and the major differences in blood glucose levels between conditions as measured with a portable blood glucose monitoring system. Riby *et al.* [18] also used a visual attention task and compared the effects of glucose and saccharin (a non-caloric sweetener). Riby subdivided the P3 into an attention component (P3a) and a memory component (P3b). Although only half of the dose of glucose commonly used in previous studies (namely 25 g) was administered, this dose gave rise to a large increase in blood glucose level measured with finger pricks

Table 1. Observational studies*

Reference	Sample	Design	Food (*post hoc*)	Measures	Main findings on P3 amplitude	Main findings on P3 latency
Geisler & Polich[12]	120 undergraduate students (60 M, 60 F; 18–23 years)	Between subjects; 5 groups measured at 08.00, 11.00, 14.00, 17.00 or 20.00 hours	0, no food; 1, drink; 2, small snack; 3, moderate meal; 4, full meal + small snack; 5, full meal + multiple snacks	Auditory oddball task (eyes closed)	Positive correlation with food score (amount of previous food ingested) ✓	–
Geisler & Polich[13]	64 undergraduate students (32 M, 32 F; 18–23 years)	Between subjects; 8 groups measured at 08.00, 11.00, 17.00 or 20.00 hours	Food group had a meal <3 h before ERP; no food group had a meal >6 h before ERP	Auditory oddball task (eyes closed)	Marginally larger in the food group	Marginally shorter in the food group
Geisler & Polich[14] experiment 1	48 undergraduate students (24 M, 24 F; 20·9 ± 2·0 years)	Between subjects; 2 groups of 12 M and F	Food group had a meal <3 h before ERP; no food group had a meal >6 h before ERP	Auditory oddball task (eyes closed)	Marginally larger in the food group	–

M, male; F, female.
*Positive main effects or interactions involving food are marked with a tick (✓), and no differences between groups indicated by a dash (–).

Table 2. Intervention studies*

Reference	Sample	Design	Food intervention	Measures	Main findings on amplitudes	Main findings on latencies
Geisler & Polich[17]	24 undergraduate students (12 M, 12 F; 22·5 ± 3·4 years)	Within subjects	Fast from 20.00 hours the previous day; 10 oz cola with 100 mg glucose† (from dextrose, no caffeine) or 10 oz bottled water at 11.00 hours	Visual oddball task before drink and at 0, 20, 40, 60, 80 min after the drink	–	–
Geisler & Polich[14] experiment 2	24 undergraduate students (12 M, 12 F; 20·9 ± 2·8 years)	Within subjects; no control condition	Fast from 20.00 hours the previous day; bread with peanut butter and jelly, apple, fruit drink at 11.00 hours	Auditory oddball task (eyes closed) before meal and at 0 and 30 min after the meal	Larger after food at 0 and 30 min after the lunch ✓	Marginally shorter at 0 min
Hoffman & Polich[16]	16 undergraduate students (8 M, 8 F; 22·5 ± 4·4 years)	Within subjects; no control condition	Fast from 18.00 hours the previous day; 2 sandwiches with 30 cc peanut butter and 15 cc jelly + apple +200 cm^3 water (about 2510·4 kJ) at 09.00 hours	Auditory oddball task (once with eyes open, once with eyes closed) before and at 60 min after breakfast	Slightly smaller after the meal	Larger after meal ✗
Hoffman *et al.*[20]	24 undergraduate students (12 M, 12 F; 22·1 ± 3·2 years)	Between subjects; 2 groups of 12 M and F	Fast from 20.00 hours the previous day; dietary supplement‡ or no fast + no supplement at 11.00 hours	Auditory oddball task (eyes closed) before and at 0, 15, 30, 45, 60, and 75 min after (no) supplement	Fast/nutrient group had marginally smaller amplitude	–
Knott *et al.*[19]	10 healthy elderly (9 M, 1 F; 62·5 ± 5·1 years)	Within subjects	Fast from midnight, 240 ml drink with 50 g glucose +4 mg saccharin or with 50·6 mg saccharin only at 08.00 hours	Sternberg memory task (with eyes open) before and 5 min after the drink	–	–
Rao *et al.*[21]	39 young adults (13 M, 26 F; 18–30 years)	Between subjects; 13 females in each group	No caffeine-containing beverages allowed on the test day; 330 ml drink with 60 g glucose and 40 mg caffeine or matched placebo at 14.00 hours	Visual oddball task (eyes open) only after the drink	Larger after the active drink ✓	Not reported
Riby *et al.*[18]	11 young adults (M and F; about 28 years)	Within subjects	Fast for 2 h; 250 ml sugar-free orange squash with 25 g glucose or with 38 mg saccharin between 09.00 and 13.00 hours	Visual oddball task only after the drink at about 30 min	P3a: –; P3b: smaller after glucose drink ✗	P3a: –; P3b: shorter after glucose drink ✓

M, male; F, female.
* Positive main effects or interactions involving food are marked with a tick (‘✓’), negative food effects with a cross (‘✗’) and no differences between groups or interventions with a dash (‘–’).
† As noted in the original paper; more likely 100 g of glucose.
‡ Meal-replacement drink 2092 kJ from fat (21·6 %), carbohydrates (64 %) and proteins (14·4 %) plus essential vitamins, minerals and trace elements at about 50 % RDA.

whereas water did not. However, no effects on attention and inconsistent effects on memory (shorter latency of the P3b but smaller amplitude) of the glucose drink were reported. The third study comparing glucose with a control intervention within the subjects was performed by Knott *et al.* [19]. This ERP study differs from the other studies by using a memory test rather than an attention test and healthy elderly rather than younger students. There was no difference in the effects of a drink with glucose plus saccharin *v.* a saccharin-only drink on memory, despite a significant rise in blood glucose level measured using finger pricks following the glucose drink.

Two additional studies compared the effects of carbohydrate interventions on attention using a between-subject design[20,21]. Hoffman *et al.* [20] found no differences in attention between a group receiving a dietary-supplement drink after an overnight fast and a non-fasted group that did not receive a dietary supplement. Rao *et al.* [21] reported that attention was improved after ingestion of a drink with added glucose and caffeine compared with a similarly tasting placebo drink, as evidenced by a larger P3 amplitude. However, as no baseline measures were taken, it is unclear whether this was a treatment effect or a pre-existing group difference.

Discussion

Although initial uncontrolled observational studies on the effects of food intake on cognitive performance measured with event-related potentials were promising, the results of studies with better experimental designs do not consistently report a positive effect. Whereas some studies reported some positive effects of foods on ERP amplitude[14,21], other studies reported no[17,19,20], inconsistent[18] or negative effects[16]. There may be several reasons for these contradictory results.

First, as some behavioural studies indicated that memory tasks such as word list recall may be particularly sensitive to carbohydrate interventions[22,23], it is possible that the lack of effects found in the ERP studies was due to the predominant employment of attention tasks. One study found no effects of glucose with a memory ERP paradigm[19], but this was a non-verbal test for digits rather than a verbal memory test. Another study by Riby *et al.* [18] reported inconsistent effects on a memory component, but this peak was elicited using an attention task.

Second, the attention tasks have been mainly aimed at one aspect of attention, namely selective attention. Moreover, they were relatively simple as evidenced by high percentages of correct responses[13,20,21]. Although for ERP a high number of correct responses is advantageous since ERP are averaged over trials with the same category of responses (usually all trials with a correct response, although error-related ERP can also be calculated), it could be worthwhile in the context of both behavioural and ERP measures to employ more difficult tests. Suggestions are multiple tasks (as suggested by Sünram-Lea *et al.* [24]) or tests requiring task switching, which are aimed at divided attention and are more complicated to perform.

From a nutritional point of view, it is difficult to make reliable inferences about the possible effects of food energy on cognitive performance assessed by ERP from these data as the level of control and detail relating to the amount and nutritional composition of the interventions is inconsistent. In addition, the studies lack a clear rationale with respect to the choice of intervention used, and to the timing of ERP measures post-consumption. In order to gain a better insight into the effects of food on cognitive performance using ERP, future studies should provide a clear rationale for the intervention used, strive to align food interventions between studies and provide a clear description of food interventions used. This should include information on the ingredient, energy and nutritional (e.g. macronutrient) composition, or at least sufficient details to allow these to be reliably estimated and accurately replicated. As a first step in this regard, it would be useful to build upon the experimental paradigms of behavioural studies wherein the positive effects of glucose interventions on cognition have been reported.

Three of the studies on carbohydrates and cognitive function reviewed earlier measured blood glucose levels in response to the intervention[17–19]. None of these studies reported a relationship between ERP amplitude or latency and changes in blood glucose level. These findings are in accordance with those from behavioural studies, in which an inconsistent relationship between cognitive performance and glycaemic response was reported[25,26]. Although blood glucose levels are linearly related to brain glucose levels under euglycaemic and hyperglycaemic conditions[27], the enzyme involved in the first step of neuronal glucose metabolism (hexokinase) is working at a maximum capacity even at low levels of neural activity[7]. Thus, increased levels of brain glucose are unlikely to alter the amount of energy directly available to neurons under normal conditions. This suggests that, although consumption of glucose and other food carbohydrates may influence cognitive performance, blood glucose itself may not be the most directly relevant marker for the underlying physiological events or their impact on cognition. It also questions the intuitively appealing hypothesis that ingested glucose improves cognition by directly increasing the uptake of glucose to the brain.

In conclusion, despite indications from behavioural studies, studies to date employing event-related potentials have not been able to add to the substantiation of evidence for cognitive-performance benefits of specific foods and ingredients. This area of research would greatly benefit from the standardisation of research methods including the use of placebo-controlled within-subject designs, more complicated cognitive tests, other cognitive tests besides attention, a clear rationale and a more systematic variation and detailed description of the choice of food interventions.

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