ABSTRACT  This article compares the findings of three studies that explored the role of increased blood glucose in improving memory function for subjects who ate breakfast. An initial improvement in memory function for these subjects was found to correlate with blood glucose concentrations. In subsequent studies, morning fasting was found to adversely affect the ability to recall a word list and a story read aloud, as well as recall items while counting backwards. Failure to eat breakfast did not affect performance on an intelligence test. It was concluded that breakfast consumption preferentially influences tasks requiring aspects of memory. In the case of both word list recall and memory while counting backwards, the decline in performance associated with not eating breakfast was reversed by the consumption of a glucose-supplemented drink. Although a morning fast also affected the ability to recall a story read aloud, the glucose drink did not reverse this decline. It appears that breakfast consumption influences cognition via several mechanisms, including an increase in blood glucose.

Am J Clin Nutr 1998;67(suppl):772S–8S.

KEY WORDS  Acetylcholine, blood glucose, breakfast, intelligence, memory, Brown-Peterson Task, Wechsler Memory Scale

INTRODUCTION  With a few exceptions (1, 2), many researchers have reported that memory improves for subjects who have eaten breakfast (3–7). The increase of blood glucose concentrations resulting from consumption of a glucose-enhanced drink has been found to improve memory in both healthy young adult (8–11) and elderly (12–15) subjects. This paper describes three studies that explored the role of blood glucose in breakfast-induced improvement of different forms of memory function.

EXPERIMENT 1: BREAKFAST BLOOD GLUCOSE AND MEMORY

Method  Benton and Sargent (3) related blood glucose concentrations to performance on two tests of memory between subjects who either did or did not eat breakfast. The subjects were 33 university students, 16 women and 17 men, with a mean age of 21.3 y. They were tested under one of two conditions: after eating their evening meal no later than 1900 h the previous evening, they either fasted the following morning or drank a beverage (Build Up; Nestle, Vevey, Switzerland) for breakfast. When the drink mix is added to 237 mL (half pint) milk, the drink provides 1370 kJ energy, 18.5 g protein, 37.7 g carbohydrate, and 12.2 g fat. By posing a series of questions, the researchers established whether most subjects habitually ate breakfast, rarely altering their usual practice. The procedure was approved by the Department of Psychology Ethics Committee, University of Wales-Swansea.

Spatial memory  The investigators placed 16 drawings of objects (eg, a dog or an apple) on a grid and instructed the subjects to concentrate for 20 s on the position of each picture on the grid. The drawings were then removed from the grid. To prevent rehearsing, they then asked the subjects to write down as many of the US states as they could remember for one minute before asking them to replace the pictures, given in random order, in their original positions. Two measurements were taken: the time taken to finish the task and the number of errors.

Word list  Three lists of 15 frequently used English monosyllabic nouns (16) were presented at a rate of one word every two seconds. Immediately afterward, the subjects wrote down as many words as they could remember. The number of words recalled and the time elapsed before the subjects gave up were recorded.

Measurement of blood glucose  Blood glucose concentrations were measured using reagent strips (Glucostic; Miles Inc, Diagnostic Division, Elkhart, NY) and a glucometer (Glucometer II; Miles Inc), which produce quantitative results comparable to accepted laboratory methods (17).

Procedure  The subjects arrived at the laboratory at 0900, had their blood glucose measured, and then randomly either ate or did not eat breakfast. After reading quietly for 2 h, they took the memory tests and their blood glucose concentrations were measured again.

Statistical analysis  The spatial memory scores were analyzed by using a three-way analysis of variance (sex of the subject, whether the subject...
ate breakfast, and whether the subject usually ate breakfast). Recall of the word list was examined by using a four-way analysis of variance (sex of the subject, whether the subject ate breakfast, whether the subject usually ate breakfast, and word list score, with the last as a repeated-measures factor). Blood glucose concentrations were related to memory scores by using Pearson’s product-moment correlation coefficient. All analyses were conducted using the SPSS statistical program (SPSS UK Ltd, Chertsey, United Kingdom).

Results

The time taken for both the spatial memory task ($F_{[1.25]} = 8.08$, $P < 0.01$) and the word list recall ($F_{[1.25]} = 5.42$, $P < 0.03$) was significantly greater when the subjects fasted than when they ate breakfast (Figure 1). All interactions were nonsignificant; however, the consumption of breakfast did not influence the number of errors on either task. For the spatial memory test, there were significant negative coefficients of correlation between the blood glucose concentrations, length of time ($r = -0.48$, $P < 0.004$), and number of errors (SEM: $-0.42$, $P < 0.01$); that is, the higher the concentration of blood glucose, the better the performance. The coefficients of correlation between word recall performance and blood glucose concentration were not significant.

It is possible that the significant correlations reflected a psychologic response to being in one experimental condition rather than the other (ie, those who missed breakfast may have been less motivated to perform well than others.) For this reason the correlations were repeated after those who ate and those who did not were separated. Two significant correlations resulted: for those who fasted, the coefficient of correlation was $-0.50$ ($P < 0.02$) between blood glucose concentrations and the time taken on the spatial memory test. For the subjects who ate breakfast, the coefficient of correlation was $-0.45$ ($P < 0.03$) between blood glucose concentrations and the number of errors on the spatial memory test. The association between blood glucose concentrations and memory performance existed irrespective of the consumption of breakfast, suggesting that individual differences in the ability to tolerate glucose are important. The blood glucose concentrations of the subjects were not particularly low: the mean values, both before and after breakfast or fasting, were never $< 4.8$ mmol/L.

Speed of recall tended to be more closely associated with breakfast and blood glucose concentrations than were the number of items correctly recalled, a finding that may reflect various mechanisms. If it does indeed indicate more rapid accessing of memory and, consequently, enhanced efficiency, then speed of recall may be seen as a more subtle measure of memory performance than the number of words recalled. An alternative explanation is that the subjects who took longer to perform the tasks were more motivated to do well. However, this explanation is less plausible because subjects who did not eat breakfast also performed the tasks more slowly.

EXPERIMENT 2: INFLUENCE OF BREAKFAST AND BLOOD GLUCOSE MANIPULATION ON THE BROWN-PETerson TASK

As noted, the first experiment found a significant correlation between memory performance and blood glucose concentrations. It was unclear from these data whether changes in glucose concentrations causally influenced memory or, alternatively, whether test performance and glucose concentration reflected a third variable, perhaps hormonal, that modulated both blood glucose concentrations and memory. The second study discussed here, now being published for the first time, systematically manipulated the amount of blood glucose in subjects who ate breakfast or did not eat breakfast, using a Brown-Peterson task (18) for this purpose. The test requires a subject to remember a trigram while counting backwards, in threes, for various lengths of time. This task has been used as a measure of short-term memory decay and information processing capacity.

Method

The subjects were 80 undergraduate women, with a mean age of 22.63 y. The choice of women only was made based on their availability for the study and on previous reports that sex differences were unimportant.

The four groups compared 1) ate breakfast and consumed a drink containing 50 g glucose ($n = 28$), 2) ate breakfast and consumed a placebo drink ($n = 25$), 3) fasted and consumed a drink containing glucose ($n = 12$), or 4) fasted and consumed a placebo drink, ($n = 15$).

The subjects followed their normal routine of eating or not eating breakfast before arriving at the laboratory at 0900. On the basis of the subjects’ meal records, the energy content of their breakfasts was calculated using food tables and standard portion sizes (19). The subjects who ate breakfast consumed a mean ($±$ SD) of 1049 $±$ 767 kJ, consisting of 42.6 $±$ 30.3 g carbohydrate, 7.2 $±$ 5.5 g protein, and 6.8 $±$ 8.4 g fat. Breakfast for most subjects consisted of cereal and milk, toast with butter or margarine and preserves, or both. The subjects gave informed written consent, and the procedure was approved by the Department of Psychology Ethics Committee, University of Wales-Swansea.

Trigrams

Forty consonant-syllable trigrams were constructed (eg, QCNR or KSF) with association values between 17% and 33% (20), according to the following criteria: a consonant appeared as the first letter of a syllable no more than twice within a list or no...
more than once in any three consecutive syllables. Alphabetical sequences were avoided.

**Glucose and placebo drinks**

The glucose drinks contained 50 g glucose dissolved in a mixture of 250 mL water and 2 tablespoons (≈36 mL) sugar-free Robinson’s Whole Orange Squash (Robinson’s, Chelmsford, United Kingdom), with 10 mL (2 teaspoons) lemon juice added to reduce sweetness. Placebo drinks contained the same ingredients with the exception of the glucose powder and the addition of 2 g Sweetex, a low-energy sweetener containing aspartame and saccharin (Crooke’s Health Care Limited, Nottingham, United Kingdom).

**Procedure**

In a double-blind procedure, the subjects randomly consumed either a glucose or placebo drink and sat quietly for 20 min before testing began. The tester then spelled out a consonant trigram, spoke a three-digit number, and asked the subjects to count backwards in threes from this number at the rate of one calculation every 2 s. When a signal light flashed after 3, 6, 9, 12 or 18 s, the subject attempted to recall the trigram. Performance in the first four trials was compared with that in the last four.

**Statistical analysis**

The percentage of trigrams recalled correctly within the first and last four trials was computed for 3-, 6-, 9-, 12-, and 18-s intervals. The effects of the drink and breakfast were analyzed using a four-way analysis of variance [whether the subject drank a placebo or glucose drink, whether the subject ate breakfast, trial 1–4 or trial 5–8, and distractor interval (3, 6, 9, 12, or 18 s), with the last two factors as repeated measures].

**Results**

Analysis of the percentage of trigrams recalled correctly revealed a three-way interaction [whether the subject had a placebo or glucose drink, whether the subject ate breakfast, trial 1–4 or 5–8] ($F_{(3,76)} = 4.98, P < 0.03$) (Figure 2). Those in the placebo group who did not consume breakfast did not significantly improve from trials 1–4 to trials 5–8. In contrast, in subjects who drank the glucose drink but did not eat breakfast before testing, performance significantly improved from trials 1–4 to trials 5–8 ($P < 0.01$). Similarly, those who ate breakfast showed practice effects whether they drank the glucose drink ($P < 0.03$) or not ($P < 0.001$). Those who did eat breakfast but drank a placebo recalled the trigrams with lower accuracy than did the other three groups. Thus, consuming a glucose drink nullified the negative consequences of missing breakfast. For the breakfast groups, breakfast consumption alone raised blood glucose concentrations, and an additional glucose drink was of no further benefit.

**EXPERIMENT 3: INFLUENCE OF BREAKFAST AND GLUCOSE MANIPULATION ON MEMORY**

To date, studies on the effect of breakfast have concentrated on measures of memory and attention, whereas other aspects of cognition have been generally disregarded. Several reports indicate that nutritional deficits can cause poor performance on intelligence tests, which can be improved with supplementation (21, 22). The third experiment, also published here for the first time, examined the effects of breakfast on both memory and intelligence test performance.
**Glucose and placebo drinks**

Both drinks were produced by Smith-Kline Beecham Consumer Products (Coteford, Gloucestershire, United Kingdom). The glucose drinks contained 50 g glucose, and the carbohydrate-free placebo drinks were sweetened with aspartame and acesulfame K. A preliminary study showed that the subjects were unable to distinguish between the two drinks.

**Procedure**

In a double-blind procedure, subjects were randomly divided into two groups that consumed either a glucose or a placebo drink, and then sat quietly for 20 min before doing the word list, Wechsler Memory Scale, and the Graduate and Managerial Assessment of Abstract Reasoning tasks. Testing took ~70 min.

**Statistical analysis**

A two-way analysis of variance was used to analyze word recall and abstract reasoning (whether the subject had a placebo or glucose drink and whether the subject ate breakfast). Preliminary analysis showed that sex did not influence the findings and, to prevent small cell sizes, it was not considered further in the analysis.

**Results**

On examination of the number of words recalled, researchers found a significant interaction between type of drink consumed and whether the subject ate breakfast (F(1,179) = 10.24, P < 0.002). Of the subjects who fasted, those who consumed the glucose drink recalled more words than those who consumed the placebo (P < 0.01). Of those who had taken the placebo, those who ate breakfast recalled more words than those who fasted (P < 0.01). However, for those who ate breakfast, the type of drink did not influence the number of words recalled (Table 1).

Those who ate breakfast recalled more of the Wechsler story (F(1,179) = 5.49, P < 0.02) than those who fasted (Figure 3). In this instance the glucose drink did not influence recall of the story (F(1,179) = 1.23, NS), regardless of whether the subjects had fasted, and there was no interaction between these variables (F(1,179) = 0.45, NS). The abstract reasoning scores indicated no effect from the drink (F(1,180) = 1.58, NS), breakfast consumption (F(1,180) = 0.61, NS), or an interaction between these variables (F(1,180) = 0.03, NS).

**DISCUSSION**

Unlike those of other organs, the brain’s energy requirements are met almost exclusively through aerobic glucose degradation. Although weighing only 2% of total body weight, the brain uses ~20% of the body’s energy at rest. The brain’s energy stores are extremely small and without glucose replacement the brain would be depleted of glucose in < 10 min. The traditional assumption that the brain is well supplied with glucose is now being questioned as a result of a series of reports indicating that raising blood glucose concentrations improves cognitive functioning.

Consumption of a glucose drink has been found to enhance memory in elderly subjects (12–15), younger adults (8–11), and animals (27). It has also been seen to improve the ability to sustain concentration in both adults (10, 28, 29) and children (30). Reaction times (31) and performance in a driving simulator (32) also improved for subjects who consumed glucose drinks.

In the studies described in this article, breakfast consumption improved performance on three memory tests (Table 1, Figures 1–3). Performance on a spatial memory test correlated significantly with blood glucose concentrations; even relatively small, diet-induced differences in blood glucose affected memory function. Our reports that breakfast consumption enhanced word list recall (Figure 1 and Table 1) and Wechsler story retention (Figure 3) confirm previous reports that eating breakfast was associated with improved memory later in the morning (1–5). Blood glucose rises after a meal, and hormonal responses in healthy individuals ensure its rapid absorption into cells. The question remains whether an increase in blood glucose associated with breakfast consumption enhances other types of cognitive functioning.

Both the present findings and previous reports (1–5) indicate that eating breakfast affects tasks that require the retention of new information. For example, breakfast did not influence performance in an intelligence test but confirmed previous findings in memory tasks. Although this topic has not been systematically explored, breakfast may influence particular aspects of memory. One distinction psychologists frequently make is between declarative and non-declarative, or procedural, memory. *Declarative memory* refers to information that can be consciously recalled and declared verbally, whereas *procedural memory* includes conditioning, habituation, and skills such as riding a bicycle. In the elderly, the ability to recall a story—using declarative memory—has repeatedly been shown to be enhanced by the consumption of a glucose beverage (12–15). An increase in blood glucose in young adults is also known to benefit declarative, but not procedural, memory (33). These studies share with ours the common finding that breakfast consumption enhances recall of stories (Figure 3) and word lists (Figure 1). Future studies are warranted to confirm the suggestion that breakfast selectively influences declarative memory.

Allowing the subjects in experiments 2 and 3 to follow their normal breakfast routine gave these studies a naturalistic quality, suggesting that breakfast, irrespective of its composition, facilitates memory. A question for future study is whether the nutritional composition of the morning meal influences memory to a greater or lesser extent. One problem with allowing subjects to choose whether to eat breakfast is the risk of self-selection: were the investigators simply measuring diurnal rhythms? Do people who eat breakfast remember more easily because they are more alert in the morning?

This concern, although reasonable, does not explain the data. The subjects in experiment 1 were randomly assigned to eat breakfast or to fast; regardless of whether the subjects normally ate breakfast, the meal improved memory. In fact, blood glucose correlated with memory even for those who had not eaten breakfast. In other studies in which fasting or breakfast consumption was decided randomly, the meal still benefited memory (2, 3).

In experiment 3, the provision of a source of blood glucose nullified the negative effects of skipping breakfast in some but not all...
higher glucose concentrations facilitate acetylcholine synthesis under conditions of increased neuronal activity. Raising glucose concentrations in mice attenuates the amnesia induced by the anticholinergic drug scopolamine (44). These animal studies are consistent with the view that, under periods of neuronal activity, raising the glucose supply is associated with an increased synthesis of acetylcholine that benefits memory.

Although there is growing evidence that glucose concentrations influence the production and release of acetylcholine, at least under conditions of demand, other factors may be involved. Given the importance of the liver in controlling blood glucose concentrations, investigators have considered the possibility that this organ may mediate the memory-enhancing capacity of glucose. Most of the autonomic nervous system messages from the liver to the brain pass through the celiac ganglion. Lesions of this ganglion decrease the memory-enhancing effect of glucose (45). It seems possible that the liver detects increases in blood glucose and sends messages to the brain. Thus, glucose may enhance memory in rodents through at least two mechanisms, one peripheral and one central.

Food intake is associated with the release of a range of gut peptides, some of which are known to have central actions. However, other mechanisms may play a role. Cholecystokinin and several other peptides are secreted by the gut in response to a meal. In the periphery, cholecystokinin is known to send signals to the brain that modulate satiety (46), and there is growing evidence that cholecystokinin may influence memory. Flood and Morley (47) found that food-related memory enhancement was attenuated by cholecystokinin receptor antagonists. Peripherally administered cholecystokinin has been found to decrease the memory of rats (48), and in vagotomized animals it may modulate memory by sending messages by way of the vagus (49). Morley et al (50) proposed that peripheral cholecystokinin enhances memory by stimulating ascending vagal fibers and hence the amygdala and hippocampus.

Researchers have considered the possibility that insulin may play a roll. Craft et al (51) suggested that the increases in insulin concentrations associated with hyperglycemia may be involved in the memory improvements observed in subjects who had consumed a glucose beverage. Although insulin is well known to stimulate glucose utilization in peripheral tissue, it was not traditionally believed to affect brain tissue. Recent studies have observed dense distributions of insulin receptors in the hypothalamus, olfactory bulb, and the CA1, CA3, and dentate regions of the hippocampus (52). These dense distributions are remarkably similar to the primary areas of pathology observed in Alzheimer disease. When Craft et al (51) raised plasma insulin concentrations in Alzheimer patients by intravenous infusion while keeping glucose at fasting concentrations, they found a striking enhancement of declarative memory. This report suggests that, at least in Alzheimer patients, insulin affects the neural mechanisms that modulate memory.

In summary, the results of the three studies discussed here indicate that the consumption of breakfast benefits memory. One of the mechanisms for this interaction involves the raising of blood glucose, although we suggest that it is not the only mechanism. It also appears that psychologic function is not uniformly affected by missing breakfast. Although certain aspects of memory seem particularly vulnerable to morning fasting, the demands placed on the brain and the nature of the memory test are important variables that require further scrutiny.

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**Figure 3.** The influence of breakfast on recall of the Wechsler story (24) in experiment 3. The data are the mean number of points recalled from a story. Those who ate breakfast recalled significantly more ($P < 0.02$).

Cases. The findings from the Brown-Peterson task (Figure 2) and the word lists (Figure 1 and Table 1) are consistent with the suggestion that the performance of subjects who missed breakfast was limited by glucose supply. However, although breakfast consumption affected recall of the Wechsler story, the glucose drink did not. This finding raises the possibility that the influence of breakfast is mediated by more than one mechanism, not by only an increase in blood glucose. We must then ask by which mechanism an enhanced provision of glucose might facilitate memory.

An association between acetylcholine-mediated neurotransmission and memory is well accepted (34–36). Acetylcholine is formed by choline acetyltransferase from the precursors choline and acetyl CoA, and glucose is the main source of the acetyl groups used in the formation of acetyl CoA (37). Because choline acetyltransferase is not a saturated enzyme, an increased supply of acetyl CoA, resulting from increased glucose metabolism, is associated with increased production. Brain acetylcholine concentrations drop after a 24-h fast in rats, but can be restored by either refeeding or administering glucose (38). Messier et al (39) reviewed the topic and concluded that, under resting conditions, increased glucose availability has little effect on acetylcholine concentrations in continuously fed animals. However, when there is a high demand for acetylcholine, such as in learning, a high availability of glucose increases the rate of synthesis of the transmitter. The postlearning period is associated with increased choline acetyltransferase activity (40) and decreased acetylcholine concentrations (41). Messier et al (39) used the uptake of choline as an index of cholinergic activity and found that injecting glucose in mice increased acetylcholine synthesis. The release of acetylcholine can be stimulated by the administration of drugs such as atropine that block presynaptic muscarinic autoreceptors. It has been shown that both an atropine-induced (42) and a quinuclidinyl benzilate-induced (43) drop in striatal acetylcholine can be diminished by a dose of glucose. Durkin et al (35), by measuring the release of glucose from a rat hippocampus, produced the first direct evidence that...
REFERENCES


