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Glucose, Exercise, and Short-term Memory
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ABSTRACT

This investigation determined the short-term memory effects of glucose and exercise. It was hypothesized that (a) glucose enhances short-term memory and (b) intense exercise diminishes short-term memory. Subjects were middle-aged volunteers who regularly exercise. Two within-subjects variables were (a) glucose vs. no-glucose, and (b) before- vs. after-exercise. A between-subjects variable was no-glucose beverage type: aspartame, saccharin, or water. Performance on Subtest IV of the Wechsler Memory Scale was the dependent variable. A glucose by exercise interaction suggested an influence of fitness level. In a second experiment, short-term memory was assessed before, and at 20-min. intervals after exercise. Weight and aerobic dance participation were treated as quasi-independent variables. Results revealed diminished short-term memory after exercise, \( F(18,3) = 9.99, \ p < .0001 \). Level of fitness affected short-term memory performance. Experimental results on exercise reflect the point at which memory is assessed as well as exercise intensity.

INTRODUCTION

Short-term memory enhancement has been a major research topic for many years. Current investigations range from uncovering the precise mechanisms by which various chemicals induce superior retention of new information to practical methods for maximizing mental function in the elderly.

Gold and associates, pioneers of memory enhancement, discovered that increased levels of plasma adrenalin were associated with improved memory for avoidance training (Gold, 1986; Gold & van Buskirk, 1975, 1976; Lee, Graham, & Gold, 1988; Stone Cottrill, Walker, & Gold, 1988) and appetitive training (Gold, Robertson, & Delanoj, 1985; Messier & White, 1984) in rats. Gold and van Buskirk (1976) determined that rats injected with adrenalin immediately after training had increased memory of what they had been taught.

Since adrenalin does not pass from blood into brain cells, researchers investigated the possibility that adrenalin acts on memory by raising plasma glucose levels (Gold, 1986; Lee et al., 1988; Stone et al., 1988). Their studies found that post-training intraventricular and subcutaneous glucose injections enhance memory. Gold, Vogt, and Hall (1986), Stone et al, (1988) and Messier and White (1987) reported evidence which suggested that the memory-improving action of glucose takes place peripheral to adrenergic receptor sites.

Glucose has been shown to enhance short-term memory in humans. Hall, Gonder-Fredrick, Chewning, Silviera, and Gold (1989) reported that short-term memory enhancement was present in college-age subjects, and effects were more pronounced in the elderly. Ballard and Lade (1990) demonstrated glucose-induced short-term memory improvements in middle-aged adults.

In many glucose studies (Ballard & Lade, 1990; Gold 1986 Hall et al., 1989) sodium saccharin was used as a control. Saccharin, a non-nutritive sweetener, had no significant effect on blood glucose level or on memory (Hall et al., 1989). Although its use has been widely accepted, concerns about the possibility of carcinogenic action in humans make finding a safe alternative to saccharin important. Aspartame (nuatrasweet) is a likely choice.

Technically, aspartame, a dipeptide, is a nutritive sweetener. However, aspartame is many times sweeter than sucrose; a much smaller quantity is needed to achieve a sweet taste (Coulombe & Sharma, 1986). Aspartame has undergone extensive testing (Caballero & Wurtman, 1988; Coulombe & Sharma, 1986; Olney, 1980; Reynolds, Butler, & Lamkey-Johnston, 1976; Reynolds, Stegink, Filer, & Renn, 1980; Stegink & Filer, 1984; Stegink Filer, & Baker, 1981 ) and is
considered safe for human consumption, even at abuse doses up to 500 mg/kg (Stegink & Filer, 1984), the equivalent of 50 pre-measured packets of Nutrasweet brand sweetener per kg body weight. Aspartame's apparent safety makes it a logical replacement for saccharin in glucose studies, provided that it has no effect on blood glucose level or on memory.

Improvement in short-term memory performance has also been associated with physical exercise. Molloy, Beerschoten, Borrie, Crilly, and Cape (1988), who studied the acute effects of exercise on mental function and mood in geriatric patients, reported significant improvement in logical memory test scores and Mini-Mental State scores measured 10 to 35 minutes following a 45 minute period of moderate exercise. They concluded that exercise has a positive effect on logical memory and increases arousal and general mental function. Their results were consistent with the findings of Diesfeldt and Diesfeldt-Groendijk (1977) and Davey, (1974) who reported sharp improvement in short-term memory performance following light to moderate exercise.

Several researchers have investigated the role of glucose in energy production during and following exercise (Ahlborg, Felig, Hagenfeldt, Hendler, & Wahren, 1974; Astrand & Rodahl, 1977; Blom, Hostmark, Vaage, Kardel, & Maehlum, 1987 Blom, Vollestad, & Costill, 1986; Cooper, Barstow, Bergner, and Lee, 1989; Coyle, Coggan, Hemmert, & Ivy, 1986; Issekutz, Birkhead, & Rodahl, 1963; Issekutz, Miller, Paul, & Rodahl, 1965; Katz & Shalin, 1990; Maughan, Fenn, Gleeson, & Leiper, 1987; Pallikarakis, Jandrain, Pirnay, Mosora, Lacroix, Luyckx, & Lefebvre, 1986; Rodahl, Miller, & Issekutz, 1964). Based on these findings, it seems likely that the effect of exercise on memory would be impairment rather than enhancement.

Glucose is a carbohydrate, one of the two primary fuels for working muscles (Astrand & Rodahl, 1977; Krogh & Lindhard, 1920). Availability of carbohydrates becomes increasingly critical as the duration of exercise increases (Bolm et al., 1986; Cooper et al., 1989; Rodahl et al., 1964). Cooper et al. (1989) found that as glycogen is progressively depleted from muscle stores, there is an escalation in whole-body glucose uptake which is increasingly reflected in declining plasma glucose levels. They confirmed the findings of Ahlborg et al. (1974) that during light exercise, 30% VO2max, arterial glucose concentrations began to fall after 40 minutes.

This describes an investigation undertaken to determine effects of glucose and exercise on short-term memory in middle-aged adults. In addition, empirical evidence supporting the substitution of aspartame for saccharin as a control was sought. The investigation was guided by the following hypotheses:

1. If glucose ingestion enhances short-term memory, then subjects will perform better on a short-term memory test after drinking glucose than after drinking a control beverage;
2. If exercise is performed at sufficient intensity and duration to significantly decrease plasma glucose level, then subjects will perform better on a short-term memory test before exercise than after exercise;
3. If aspartame ingestion elevates plasma glucose levels, then subjects will perform better on a short-term memory test after drinking aspartame than after drinking water or saccharin.

Experiment 1
Method
Pilot Studies
A preliminary investigation of effects of glucose and exercise on short-term memory was made. A 2 X 3 split plot design was employed, and 15 middle-aged female volunteers were randomly assigned to three beverage groups, glucose, aspartame, and water. Paired associate test results revealed trends in support of the glucose and exercise hypotheses and suggested a possible negative effect for aspartame, which indicated that more rigorous control of blood glucose level was necessary.
The effect of glucose, aspartame, and saccharin on plasma glucose level was measured in a second study using repeated measures with 17 middle-aged volunteers. Results indicated that only glucose ingestion significantly elevated blood glucose level, \( M = 140.86 \text{ mg/dl} \) vs. saccharin, \( M = 85.64 \); aspartame, \( M = 91.86 \); and water, \( M = 76.36 \). The slight elevation in blood glucose after ingestion of saccharin and aspartame were not significantly different from blood glucose level after drinking water.

**Design**

Experiment 1 employed a 2 X 2 X 3 split plot design. Within-subjects variables were: (a) glucose vs. no-glucose control, and (b) before- vs. after-exercise administration of a beverage and short-term memory test. The between-subjects variable was the type of no-glucose beverage used: aspartame, saccharin, or water.

**Subjects**

Participants in the experiment were volunteers, a total of 16 males and 16 females who regularly exercise. Their ages ranged from 29 to 53 years. The mean and median age was 38. Groups were matched for age and type of exercise performed.

**Materials**

The four beverages used were three sweet lemon-flavored solutions and water. The glucose solution was composed of 50g glucose (Polycose brand glucose polymers) in 250 ml water and .05g unsweetened lemon-flavored Kool-Aid brand soft drink mix. The aspartame solution was composed of 2g Nutrasweet in 250 ml water and 0.5g unsweetened lemon-flavored Kool-Aid. The saccharin solution was composed of 48 mg sodium saccharin in 250 ml water and 0.5g unsweetened lemon-flavored Kool-Aid. The three lemon-flavored solutions were mixed and re-mixed until reliable judgements about glucose vs. aspartame vs. saccharin were not made by naive subjects.

**Instruments**

Subtest IV from Form I and Form II of the Wechsler Memory Scale was used as the short-term memory assessment tool (Molloy et al., 1988). Subjects listened to a single presentation of an audio taped narrative passage. Following a 15 sec. delay, subjects were asked to repeat the passage from the beginning. The score was the number of ideas accurately recalled. The order of presentation of the four tests was counterbalanced.

Heart rate was monitored using a Monarch brand Trim Guide 2000 Calorie and Heart Rate Monitor, model 6200. Target exercise heart rate was computed for each subject based on 50\% of heart rate capacity calculated from the resting heart rate and adjusted for age using Hoeger's (1989) formula: \([ (220 - \text{Age} - \text{Resting Heart Rate}) \times 0.5 ] + \text{Resting Heart Rate} = \text{Target Heart Rate}\).
exercise. After another 15-min. wait, a second short-term memory test was administered, following the second session subjects were debriefed.

**RESULTS**

Two subjects' data were eliminated from analysis due to failure to attain target heart rate. Data were analyzed in four steps using MANOVAs.

The first step tested for equivalent difficulty of the short-term memory tests and order-of-presentation effects, mean scores for each test by the four orders of presentation used. Homogeneity of variance was attained, and there were no significant differences between mean scores. This showed that tests were essentially equal in difficulty, and there were no effects due to the order of presentation of the tests.

Second, subjects' short-term memory test scores were analyzed by order (whether glucose was administered in the first session or the second) and by control (which of the three control beverages was used). There was a significant interaction, $E(72,3)=26.865$, $p<.001$, indicating that how subjects scored depended on whether they had consumed glucose or one of the control beverages and whether the test was before or after exercise. Subjects who drank glucose in the first session did not score significantly differently from subjects who drank glucose in the second session. Likewise, short-term memory test performance of subjects who drank a control beverage in the first session did not differ significantly from that of subjects who drank a control beverage in the second session.

Third, because the previous analysis showed that there was no significant effect for the different types of control beverages, the control variable was collapsed and short-term memory test scores were analyzed by type of beverage, glucose or control. There was a significant glucose effect, $E(84,3)=26.245$, $p<.001$. Mean short-term memory test scores (number of ideas recalled) for the glucose condition were significantly higher, 14.3 before exercise and 13.5 after exercise, than mean short-term memory test scores for the control condition, 9.6 before exercise and 10.1 after exercise.

The fourth analysis revealed no significant main effects for exercise whether subjects drank glucose before and after exercise or whether they drank control beverage before and after exercise.

However, there was a beverage type by exercise type effect, $E(60,12)=2.059$, $p=.034$. Subjects' short-term memory test scores depended on which type of exercise they performed and whether they drank glucose or a control beverage (see Figure 1). Post hoc Duncann's Multiple Range Test revealed that short-term memory performance of subjects who used the stair-stepping machine was significantly better after exercise than before exercise whether the beverage consumed was glucose (16.8 ideas after exercise vs. 13.7 before) or a control (11.3 ideas after exercise vs. 8.5 before). However, the short-term memory performance of subjects who walked was significantly poorer after exercise, but only when the beverage they consumed was glucose (11.1 ideas after exercise vs. 13.7 before exercise). In both beverage conditions, stair-stepping machine subjects' and walking subjects' pre-exercise memory scores were significantly different, but their post-exercise short-term memory scores were significantly different, (16.8 ideas vs. 11.1 respectively in the glucose condition; 11.3 ideas vs. 8.1 respectively in the control condition).

![Figure 1. Results of Experiment 1 showed an interaction, beverage type by pre- vs. post-exercise memory scores, between walking subjects and stair machine subjects.](image-url)
DISCUSSION

Two goals were accomplished by this experiment. First, aspartame is valid for use as a control. Contrary to the hypothesis, aspartame did not elevate plasma glucose levels, and there were no significant differences between mean short-term memory test scores following ingestion of aspartame, saccharin, and water. When a sweet-tasting control is needed, aspartame is equally as useful as saccharin.

Second, glucose enhancement of short-term memory was replicated in middle-aged adults precisely as hypothesized. Since this effect is well established in the literature, research is now directed toward discovering the mechanism by which glucose enhancement is accomplished.

Messier and White's (1987) peripheral glucose transport hypothesis is supported by their finding that fructose, 2-deoxyglucose, and 3-O-methylglucose improved memory retention although none elevated plasma glucose level. It appears that plasma glucose level is not critical to memory enhancement. Since fructose does not cross the blood brain barrier, it is likely that both glucose and fructose act peripherally. Memory enhancement by 2-deoxyglucose, which cannot be metabolized, and by 3-O-methylglucose, which can be only partially metabolized, suggest that glucose memory enhancement depends on activation of a membrane glucose transport mechanism rather than glucose metabolic processes.

This experiment also produced an intriguing interaction. Although the walking subjects' impaired post-exercise short-term memory performance marginally supported the hypothesis, the stair-stepping machine subjects' improved post-exercise short-term memory performance is consistent with the literature (Molloy et al., 1988; Davey, 1974). Subjects who used the stair-stepping machine and subjects who walked comprised the only two exercise groups in which an identifiably homogenous level of fitness was exclusively represented. Stair-stepping machine subjects were well-conditioned athletes who were active in a number of intensive sports and training methods; however, the walking subjects were individuals whose only mode of exercise was walking. A second experiment was conducted to clarify this influence of fitness.

Experiment 2

METHOD

Subjects

Eight females in an aerobic dance class at a fitness club volunteered to participate in the experiment. They ranged in age from 30 to 58 years. Their mean age was 39 and their median age was 33.

Design

A repeated-measures design assessed short-term memory before, immediately after, 20 min. after, and 40 min. after exercise. Age, weight, percent of body fat, and length of time participating in an aerobic dance class were treated as quasi-independent variables.

Instruments

The same short-term memory measure employed in Experiment 1 was used. A single presentation of a brief narrative passage was read aloud by the experimenter, following which the subject repeated the story from the beginning. The score was the number of ideas accurately recalled. The order of presentation of the 4 tests was counterbalanced across subjects.

In addition, subjects submitted individual fitness and demographic information forms administered by the fitness club.

Exercise Protocol

The mode of exercise was an aerobic dance class consisting of a five-minute warm-up, 33 minutes of intense aerobic dancing at 80-85% of the subject's maximum heart rate, followed by a 2-min. cool down. Each subject's target heart rate was computed by the fitness club using Algra's (1985) Target Heart Rate Training
Chart. Subjects monitored their own heart rates at approximately 5 min., 15 min., and 30 min. from commencement of exercise by obtaining a 10 sec. pulse count taken at the carotid artery.

Procedure

Each subject was tested individually, 2 subjects per session, in a total of 4 sessions. First, subjects were presented with an outline of the procedure, and instructions for the short-term memory tests were explained. Next, the pre-exercise memory test was given. Subjects then participated in a 40-min. aerobic dance class. Immediately following the class a second memory test was administered. Subjects were then allowed to proceed with their usual cool down and muscle toning routine. This routine was interrupted at 20 min. and 40 min. from the end of dance class for the administration of the third and fourth memory tests. Following collection of data from all 8 participants, subjects were debriefed.

RESULTS

Multivariate analysis of variance was computed to analyze the effect of the point of testing on short-term memory scores. There was a significant main effect for time, F(18,3)=9.99, p<.001, indicating that subjects' short-term memory test scores were influenced by the time at which memory was measured. Exercise had an immediate negative effect on short-term memory scores (M = 13.5 ideas before exercise vs. 9.75 ideas immediately after exercise), following which memory performance regressed toward the pre-exercise level as subjects recovered from the exertion, (12.5 ideas 20 min. after exercise, and 13.5 ideas 40 min. after exercise).

The second MANOVA, short-term memory scores by subject's weight, median split, produced a significant interaction by weight and by time, F(18,3)=5.419, p=.008. Subjects with lower body weight recovered much more quickly from the negative exercise effect than subjects with higher weight (see Figure 2). By 20 min. after exercise, lower-weight subjects' short-term memory scores had returned to pre-exercise values; however, higher-weight subjects' short-term memory scores did not return to pre-exercise values until 40 min. after exercise.

Similarly, the third MANOVA, short-term memory scores by length of time subjects had participated in aerobic dance, median split, revealed a significant interaction, F(18,3)=3.35, p=.042 (see Figure 3). Those subjects who had participated in aerobic dance classes 36 months or longer recovered from the exercise effect by 20 minutes, whereas those who had participated in aerobic dance classes 24 months or less required 40 minutes to recover from the exercise effect.

The analysis of short-term memory scores by age and by percent of body fat revealed no effects due to either factor.
GLUCOSE, EXERCISE, AND SHORT-TERM MEMORY

DISCUSSION

Short-term memory scores immediately following exercise were profoundly lower than pre-exercise memory scores, precisely as hypothesized. Exercise performed was of sufficient duration and/or intensity to significantly lower circulating plasma glucose, consistent with Cooper et al. (1989) and Ahlborg et al. (1974). This experiment demonstrated that reduced availability of circulating glucose negatively affects short-term memory performance.

Recovery from the exercise effect reflected the subjects' level of physical fitness. Subjects with higher levels of fitness, those with longer participation in aerobic dance classes and lower body weight, performed significantly better than less fit subjects, those with shorter participation in aerobic dance classes and higher body weight, on the short-term memory test administered 20 minutes after exercise.

A primary benefit of a high level of physical fitness is efficient use of oxygen, The supply of oxygen to working muscle cells determines the percentage of fats vs. carbohydrates utilized in energy production (Astrand & Rodahl, 1977). When oxygen availability is high, metabolism of free fatty acids (FFA) is facilitated because oxidation of FFA depends on oxygen as the hydrogen acceptor. When oxygen availability is low, usable fuel is restricted to carbohydrates, which are limited in supply (Astrand & Rodahl, 1977), ultimately causing significant declines in plasma glucose levels as exercise is prolonged (Cooper et al., 1989).

Physical training which increases VO$_2$ uptake also increases the facility for fat metabolism (Issekutz et al., 1965). The greater the VO$_2$ uptake at a given workload, the greater the percentage that fat contributes to energy metabolism. It seems logical that, in Experiment 1 and Experiment 2, subjects' differing levels of fitness resulted in differences in plasma glucose level. Less fit subjects metabolized carbohydrates, perhaps exclusively, during exercise, reducing plasma glucose levels more sharply than more fit subjects who could metabolize more fats and spare plasma glucose. These differences in plasma glucose level account for the differences in short-term memory scores at 20 minutes after exercise in both experiments.

Studies of the effects of exercise persistently use well conditioned athletes as subjects (Blom et al., 1987; Blom et al., 1986; Cooper et al., 1989; Coyle et al., 1986; Maughan et al., 1987; Pallikarakis et al., 1986; Peters Futre et al., 1987). Care must be exercised when generalizing results to less fit individuals.

GENERAL DISCUSSION

Administration of oral glucose while assessing the effect of exercise on short-term memory had a confounding effect, changing the extent to which glycogen stores were metabolized, possibly distorting memory scores recorded during the glucose condition.

Issekutz et al. (1963) found that carbohydrate intake immediately before exercise causes a utilization shift toward carbohydrate metabolism with a corresponding reduction in FFA metabolism. In addition, Pallikarakis et al. (1986) found that glucose ingested at the rate of 50g per 30 min. covered 85-90% of the total carbohydrate utilization during 60 minutes of moderate exercise, significantly sparing both circulating glucose and glycogen stores. The fact that Experiment 1 used a glucose polymer concentrate further confounded the experiment.

Maughan, et al. (1987) compared the effects of dilute glucose/electrolyte solution to concentrated glucose polymer solution during and after exercise. Though they found no significant differences in plasma glucose level during exercise, by 15 min. after exercise, subjects who had consumed the glucose polymer concentrate experienced a dramatic increase in plasma glucose level over plasma glucose level during exercise and over subjects who consumed the glucose/electrolyte beverage.

This study has identified several issues for consideration in future research.
One interesting comparison would be carbohydrate metabolism vs. fat metabolism during exercise in athletes with high-fat bodies (e.g. English Channel swimmers) and low-fat bodies (e.g. marathon runners). Second, since it is likely there were significant differences in blood glucose level between highly fit subjects and less fit subjects in this study, monitoring blood glucose level across fitness levels could contribute information not assessed by Cooper et al. (1989). Third, Astrand and Rodahl (1977) insist that direct measurement of VO\textsubscript{2}max is superior to either heart rate or VO\textsubscript{2}max estimates in determining differences in work level intensity, and is the preferred method for research in which homogenous exercise intensity groups are required.

In conclusion, this study achieved its initial goals: glucose modulation of short-term memory was successfully replicated, aspartame was established as a valid control, and a profound negative effect for exercise on short-term memory was revealed. This study suggested that both the negative exercise effect and the exercise interaction are not inconsistent with existing literature which report enhancement of short-term memory after exercise, but rather reflect the point at which memory is measured. Recovery from the negative exercise effect appears to be a function of the level of fitness, more particularly, efficient use of oxygen. Although attempts to maintain ecological validity created confounds, the primary results were not compromised. In future assessments of the effect of exercise on memory, administration of glucose is contraindicated. In addition, both food ingestion and level of fitness should be controlled.

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GLUCOSE, EXERCISE, AND SHORT-TERM MEMORY


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