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Dietary Effects on Cognition and Pilots' Flight Performance

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Abstract

The purpose of this study was to investigate the effects of diet on cognition and flight performance of 45 pilots. Based on a theory of self-care, this clinical study used a repeated-measure, counterbalanced crossover design. Pilots were randomly rotated through 4-day high-carbohydrate, high-protein, high-fat, and control diets. Cognitive flight performance was evaluated using a GAT-2 full-motion flight simulator. The Sternberg short-term memory test and Vandenberg's mental rotation test were used to validate cognitive flight test results. Pilots consuming a high-protein diet had significantly poorer ($p < .05$) overall flight performance scores than pilots consuming high-fat and high-carbohydrate diets.

The effects of nutritional status and dietary intakes on performance have been debated since Florence Nightingale's work for the British Army during the Crimean War (Nightingale, 1860). There is even greater interest today with a growing awareness of nutrition's role in promoting health and preventing disease. It is generally accepted that pilots who eat a well-balanced diet perform better, have increased energy levels, and have longer endurance (Copp & Green, 1991; Downey, 1983; Hart & Morrison, 1992). Recently, specific macronutrients necessary for increased performance and endurance have been identified (Fischer, Colombiani, Langhans, & Wenk, 2001; Greenwood, 2003; Greenwood & Winocur, 2005; Halyburton et al., 2007; Kaplan, Greenwood, Winocur, & Wolever, 2000; Sunram-Lea, Foster, Durlach & Perez, 2004).

Few published clinical trials have confirmed the effects of diet and nutrition on pilot performance, although some studies have found that cognitive performance is related to diet (Benton et al., 2003; Fischer et al., 2001; Lieberman, Wurtman, & Chew, 1986a; Spring, 1984, 1986). Furthermore, although the positive effects of a balanced diet and eating healthy

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foods at appropriate times might affect pilot performance, the effects of diet on performance are often overlooked (Bourre, 2006; Ferrar, Bisson, & French, 1995; Fisher & Atkinson, 1980). With an overall goal to continually increase aviation safety, this study aimed to identify dietary factors that affect flight performance and cognition.

BACKGROUND

A well-balanced diet provides the body with essential nutrients needed to build and maintain cells, to regulate bodily functions, and to supply energy. The role of dietary intake and nutritional status in sustaining health and preventing disease is also well documented. Studies of U.S. Air Force pilots (Copp & Green, 1991; Hart & Morrison, 1992) and of civilian pilots (Lindseth & Lindseth, 1995) found these pilots were often at greater safety risk because they tended to have unstructured eating patterns, contributing to inadequate intake of certain nutrients. However, these reports focused on the nutritional intake of the study populations rather than on the cognitive performance relationship.

Nutrient intake plays a crucial role in the functioning of the nervous system and, therefore, behavior (Yehuda, Rabinovitz, & Mostofsky, 2005). “Deficiencies in intakes of a number of vitamins and minerals are accompanied by impairments in brain functioning and behavioral disturbances” (Kanarek, 1997, p. S105). Ferrar et al. (1995) emphasized, “Specific meals and the proper timing for those meals can positively affect mission performance” because “the ‘human machine’ requires the proper fuel at the proper times to accomplish its mission” (p. 574). For example, the popular anti-jet-lag diet proposes that fasting or eating certain foods can be used to prevent flight fatigue (Ferrar et al.). However, human trials are needed to confirm that dietary recommendations are helpful.

It has been suggested that elevating serotonin levels with a diet rich in carbohydrates can induce sleep, and that elevating catecholamine levels with a diet high in protein can promote wakefulness (Ferrar et al., 1995). High-carbohydrate meals increase tryptophan levels, which are associated with increased levels of serotonin in the brain. Eating a high-protein diet can result in an increase in the amino acid tyrosine, which can be converted to catecholamine and can enhance norepinephrine levels. This should improve mental and physical performance, according to Owasoyo, Neri, and Lamberth (1992). However, adjusting consumption of macronutrients such as proteins, carbohydrates, and fats has produced mixed results in terms of correlating diet with cognitive performance (Smith & Kendrick, 1992). There is thus a need to study the effects of diet on cognition and flight performance.

Reaction times can also differ depending on the consumption of macronutrients (Greenwood, 2003; Kaplan et al., 2000; Smith & Kendrick, 1992). Cognitive improvement has been observed after brief (single-meal) interventions. Specifically, carbohydrate ingestion resulted in relatively better short-term memory and accuracy in performing tasks concomitant with higher metabolic activation. Also, better cognitive performance has been associated with glucose-based diets (Sunram-Lea et al., 2004). However, other research showed that protein-poor, carbohydrate-rich meals elicited greater performance deterioration than did isocaloric protein-rich meals (Lieberman et al., 1986a; Markus, Panhuysen, Jonkman, & Bachman, 1999; Markus et al., 1998; Spring, 1986). Additional research is needed to clarify the effects of nutrition on flight performance and cognition.

Consequently, the purpose of this study was to (a) analyze for differences in flight performance and cognition scores among groups of pilots receiving a high-protein diet, a high-fat diet, a high-carbohydrate diet, and a nonmanipulated (control) diet; and (b) examine for relationships of participants' cognitive and flight performance scores to their dietary intakes while controlling for demographics, health status, sleep and activity levels, anxiety, and related environmental factors.

METHODS

Study Design

This clinical study used a randomized crossover design model in which 15 participants per academic term were brought through study protocol, for a total of 45 participants. Prior to treatment, each participant received a health assessment, had anthropometrical measurements taken, completed a food frequency questionnaire, and provided demographic information. Each pilot was randomly rotated through each of three treatment diets—and received 4 days of prepared meals consisting of high protein (56% protein, 22% carbohydrate, 22% fat), high carbohydrate (56% carbohydrate, 22% fat, 22% protein), and high fat (56% fat, 22% carbohydrate, 22% protein). In addition, each of the pilots served as his or her own control and received a 4-day control diet (50% carbohydrate, 35% fat, and 15% protein). Food consumption was controlled for nutrient content and was within 5% of the U.S. recommended daily allowance (RDA). All meals were prepared under the direction of a registered dietitian and were served to the study participants by the research team. The dietary interventions were double-blinded because neither the participant nor the aviation researchers knew when the participant was receiving the control diet or the treatment diets. To test for possible relationships to pilot cognition and flight performance scores, each macronutrient (i.e., protein, carbohydrate, and fat) was tested ("treatments") and the other nutrients were kept constant. For example, when dietary fat intakes were being tested, protein intakes were held constant. The test results from pilots on each diet, including the control diet, were compared. Pilots were followed from study entry through the three dietary treatments and control diet; observation ended after the cognition tests and flight performance observations were completed. The potential effects of order of treatment were mitigated in two ways: First, 2 full weeks elapsed between treatments; and second, treatment order was assigned randomly to the participants.

Population Description and Sampling Plan

Study participants were recruited from a group of pilots enrolled in a large collegiate aviation commercial pilot curriculum. Participants included in the study protocol all held current Federal Aviation Administration medical certificates for flying and met the following selection criteria: (a) were enrolled in the third-semester course of a commercial pilot aviation course of study; (b) had given informed written consent to participate in the study; (c) were 18 to 40 years of age; and (d) were able to read, understand, and speak English.

A power analysis using Borenstein, Cohen, and Rothstein's (1997) *Power & Precision* software was used to determine the sample size needed. The power analysis calculation was based on the use of multiple analysis of variance (ANOVA) statistics. Possible effects of dietary interventions on the groups of pilots were based on information gathered from a preliminary study of diets and pilots and other relevant publications. The power analysis estimated the effect size to be medium. The power for this sample calculation was set at .80, with alpha = .05. Therefore, a minimum of 35 participants was needed in each treatment group to achieve statistical power. Ten additional participants were entered into the study to allow for a conservative estimate of 30% of the participants who might not be able to participate or who would drop out due to attrition. Therefore, a total of 45 individuals were recruited for the study. All participants served as their own control, and each pilot rotated through the three treatment groups. Prior to starting the study, the protocols were initially tested using 14 individuals.

Dietary Treatments

The three dietary treatments used in this study consisted of a 4-day high-protein diet, a 4-day high-carbohydrate diet, and a 4-day high-fat diet, plus a 4-day control diet. Both food consumption and food preparation were controlled. The treatment diets were prepared by a registered dietitian in consultation with the study investigators.

Food consumption was controlled both in terms of what was consumed and how much was consumed. An initial educational session informed each pilot of the importance of dietary compliance to obtain accurate study results. Each pilot was served special prepared meals for each 4-day session on the control diet or on one of the treatment diets. According to Gibson (1990), the most accurate method for quantifying someone's food ingestion is by weighed food intakes. The quantity of food apportioned to each participant was weighed before and after eating by the dietitian. Portions were determined by measuring the pilots' kilocalories per day, based on indirect calorimetry results to determine the participants' appropriate calorie levels. A computerized metabolic monitor was used to determine the indirect calorimetry measures. The pilots were served beverages as part of their meals. The amount of caffeine consumed was carefully controlled because of the possible effects on cognitive performance. Bottled water was issued to the pilots with a request that all bottles and remaining contents be returned. Pilots were given snacks to take home for consumption between the evening meal and breakfast. Other than snacks, all foods were eaten in the study dining room. After consuming each meal, the pilots were questioned to be certain that they did not consume foods and beverages that were not issued by the study.

Data Collection

The participants' demographic data were recorded, including age, educational level, marital and social living status, ethnic identification, and flight and instrument times.

Biochemical and laboratory data were also recorded, with serum glucose levels being closely monitored to check for possible hypoglycemic episodes or glucose intolerance that might occur during flight. Licensed personnel collected all lab tests.

To control for anxiety, the Self-Rating Anxiety Scale (SAS) was used to quantify each participant's anxiety level (Zung, 1980). A 20-item questionnaire was administered to the pilots asking them to rate the items as they applied to the participants within the past 24 hr. Anxiety severity was rated on a scale from 1 to 4, with a 4 representing the most severe anxiety level and a 1 representing the lowest anxiety level. The alpha coefficient for reliability of this scale was .78 in a study of pilots (Zung, 1980).

Pilots were measured for cognitive flight performance using a flight motion simulator (the GAT-2 simulator manufactured by Environmental Tectronics Corporation). All pilots were tested in the same flight motion simulator with simulated flight conditions and aircraft status standardized for all participants. The evaluated flight performance tasks were airspeed control, heading control, and altitude control. Total flight hours and instrument time were recorded for each participant. Environmental factors controlled during the flights included turbulence (no turbulence) and weather. Weather was controlled in instrument meteorological flight conditions for the duration of the performance evaluation. The temperature of the simulator cockpit was maintained at between 70°F and 74°F, and a thermometer in the cockpit recorded the exact temperature of each pilot's flight. A wireless sound level meter was used to measure cockpit noise levels because of the possible effect or interference by noise with cognition and performance.

The Sternberg short-term memory test (Sternberg, 1966) and the Vandenberg mental rotation test (Peters et al., 1995) were used to measure cognition and to validate the cognitive flight performance testing used for this study. The coefficient alpha reliability index of the Sternberg instrument was .86 when used with the pilots. Spatial cognition was evaluated using the Vandenberg Test of Mental Rotation. The Kuder–Richardson internal consistency coefficient was .62 when testing the reliability of the Vandenberg Test of Mental Rotation with the pilots.

Health assessment data for each pilot were recorded using Doenges's Health Assessment Checklist (Doenges, 1989). Nine factors were assessed according to the Doenges checklist, including history of chronic systemic disease (heart disease, hypertension, respiratory insufficiency, and diabetes), metabolic or gastrointestinal disorders, and urinary or neurological disorders.

Sleep and activity workloads were measured using an Actiwatch sleep watch system to monitor the participants during dietary treatment periods. This device was similar in size and shape to a wristwatch and recorded gross motor activity (Ancoli-Israel et al., 2003). Sleep and wake patterns, fatigue and alertness, bed and rise times, sleep efficiency, sleep and wake patterns, mean activity scores, and other activity patterns were measured while the participant wore the device. The Actiwatch can interface with a computer and provide analyzed data via a printed data summary. This helped provide uninterrupted observations of activity levels as well as provided a portable means of collecting the study data. A reliability of alpha = .88 was determined for the data collected by this device (Ancoli-Israel et al., 2003).

Anthropometric data were documented for each subject including serial weights and body mass index (BMI) measurements. BMIs were further calculated for the pilots using the Quatelet Index (kilograms/meters^2), a weight to height ratio based on the pilot's weight at entry into the study (Gibson, 1990).

Procedures

The purpose and details of the study were explained to prospective commercial pilots at an arranged meeting, and researchers answered the pilots' questions. Individuals who wished to participate signed informed consent forms and completed questionnaires about demographic information. Their base kilocalorie levels were calculated using indirect calorimetry. Laboratory data, anthropometric measures, and environmental measures were collected by the researchers or by the research assistants during scheduled appointments.

Dietary treatments were the key intervention for this study. All food intakes were weighed by the research team prior to consumption as well as after consumption to determine the amount of food eaten by each study participant. From these weight measurements, nutrient intakes were calculated for each of the diets. Cognitive flight assessments using 20-min flight simulation scenarios and testing of short-term memory and spatial orientation were obtained on the fourth day of each diet treatment session. Flight and cognitive testing was completed within 2 hr of the pilots consuming their final meal of the treatment week. Sleep and activity levels measured by the Actiwatch were also recorded on the fourth day of the treatment period.

Data Analysis

The Statistical Package for Social Sciences (SPSS) and the SPSS Explore procedure were used in the data analysis process. Analyzed measures included cognition and flight performance, dietary intakes, demographics, laboratory values, sleep and activity levels, anxiety levels, and related environmental factors. These data were analyzed by descriptive and inferential statistics including correlational analysis and ANOVA. Multiple regression analysis was used to determine predictiveness. The potential effects of confounding variables were controlled through hierarchical entry into a multiple regression equation. The level of significance was established at $p \le .05$.

Nutrient analyses of the weighed food intakes were completed with the Food Processor Analysis System (ESHA Research, 2000). This system is a computerized dietary analysis package that can analyze an extensive nutrient list and measure both macronutrient and micronutrient intakes of food based on the U.S. RDA.

Sample Characteristics

Forty-five pilots including European American, Asian, Hispanic, and African American pilots completed this study. Pilots were from 22 different American states and one foreign country. Data summarizing the sample characteristics are shown in Table 1.

RESULTS

Flight Performance Scores

An overall flight performance score was based on deviations from perfect airspeed, altitude, and heading readings for the entire flight scenario. Table 2 shows the repeated-measures ANOVAs used to determine whether there were significant differences in cognition and flight performance scores when comparing the four dietary treatment groups. The statistically significant differences shown in Table 2 were based on a comparison of overall flight performance scores, as well as comparisons of altitude, heading, and airspeed scores, in groups of pilots on each treatment diet and on the control diet.

A repeated measures ANOVA was performed for each variable. A significant effect was observed in deviations from altitude, $F(3, 42) = 5.7$ ($p \leq .01$). A subsequent post-hoc analysis (Fisher's least significant difference test) revealed that the high-fat treatment group ($p \leq .001$), the high-carbohydrate treatment group ($p \leq .01$), and the control diet group ($p \leq .01$) made significantly fewer errors than the high-protein treatment group. The number of errors for altitude, heading, and airspeed (overall flight performance scores) were analyzed using a repeated measures ANOVA, resulting in a significant effect, $F(3, 42) = 3.08$, $p \leq .05$. A subsequent post-hoc analysis test indicated that both the high-fat and high-carbohydrate groups made significantly fewer errors than the high-protein group.

Vandenberg's Mental Rotation Test Results and Sternberg Results

The Revised Vandenberg and Kruse Mental Rotation Tests (MRT) were administered on the fourth day of each diet session. The Vandenberg test was scored based on the number of correct answers to 24 problems. Each problem was scored as correct if the respondent picked two of the four response alternatives that matched the target figure. A one-way ANOVA for the Vandenberg test revealed no significant differences between the diets.

The results of the Sternberg testing were complicated. Diet had no observable impact on positive (yes) decisions, but impacted negative (no) decisions on memory set sizes four and six. For memory set sizes of four and six digits, the high-fat diet group had the fastest response size latencies. No impact of the diets was observed on positive decisions in the Sternberg test, whereas high-fat diet was superior to high-protein diet for negative decisions. An examination of the slopes and means suggest that response times were faster for participants when fed the high-fat diet, especially at higher memory loads.

Validation of Cognitive Measures

The following correlations validated the cognitive measures used. Airspeed mean deviation scores correlated significantly with Sternberg test performance ($r = .24$, $p < .01$) and mental rotation test performance scores ($r = -.33$, $p < .01$). Altitude mean deviation scores correlated significantly with Sternberg test performance ($r = .18$, $p < .05$) and mental rotation test performance ($r = -.24$, $p < .01$). The Sternberg test performance scores also correlated significantly with the mental rotation test performance ($r = -.23$, $p < .01$). Although these correlations are statistically significant, they are not very predictive of performance. Consequently, further study is recommended.

DISCUSSION

In this randomized, counterbalanced, crossover design study, three sample treatment diets and a control diet were used to examine the effects of dietary intakes on flight performance and cognition in a group of 45 pilots. Data collected from these groups indicated flight performance scores for pilots consuming high-fat diets and high-carbohydrate diets were significantly better ($p < .05$) than scores for pilots consuming high-protein diets. The Sternberg results indicated that the scores of pilots on the high-fat diet were significantly better than the performance scores of pilots on the high-protein diet.

Protein-rich meals resulted in poorer flight performance scores than did the high-fat and high-carbohydrate diets. The Vandenberg MRT test results showed no significant differences among pilots on the four diets. Although the Sternberg short-term memory test results were mixed, they showed some agreement with the overall flight performance data. Specifically, the high-fat diet group showed significantly better response scores than the other dietary groups, thus showing some agreement with the overall flight performance data. Also, the high-fat diet group had significantly better overall flight performance scores than the high-protein diet group. Furthermore, both the Sternberg and Vandenberg MRT test results correlated significantly with overall flight performance scores. Thus, these results showed a relationship between the pilots' flight performance and commonly used cognition testing measures.

Previous research on this topic has been inconsistent, and results have been mixed. For example, according to Smith and Kendrick (1992), adjusting the quantities of macronutrients such as proteins, carbohydrates, and fats has produced conflicting results in terms of correlating diet with cognitive performance. Some earlier studies contradict the findings of our study. For example, with respect to cognitive performance, an earlier study found that diet had significant effects on reaction time (Smith & Kendrick, 1992). When differences in the composition of the meal were studied, cognitive performance was better after a higher protein breakfast (Spring, Pingitore, Bourgeous, Kessler, & Bruckner, 1992). A large three-course lunch (with more calories) significantly increased errors on attention tasks. The largest drop in performance was found for participants who ate a big lunch but were accustomed to eating a light lunch, whereas a light lunch did not cause a postlunch dip in performance. The macronutrient composition of the meal also influenced the likelihood of a postlunch dip. Protein-poor, carbohydrate-rich meals elicited greater performance deterioration than did isocaloric protein-rich meals (Kennedy, Fowlkes, & Lilienthal, 1993; Lieberman et al., 1986a, 1986b; Spring, 1984, 1986). In addition, a low-protein, high-carbohydrate lunch tended to induce slower reaction times, vigilance impairment, and decrements in sustained attention (Spring, 1984). Further, attention task studies showed that individuals consuming high-fat meals responded more slowly but still accurately to cognitive performance tests (Spring, Maller, Wertman, Digman, & Coliozo, 1992). Finally, some studies showed that high fat intakes by individuals resulted in impaired cognitive performance (Greenwood & Winocur, 2005; Lloyd, Green, & Rogers, 1994). These findings were not consistent with our results.

However, the results of other studies are in agreement with the results of this study. For example, researchers in Toronto examined whether carbohydrate-rich, protein-poor foods negatively affected cognitive performance. A strong relationship was found between dietary carbohydrates and enhanced cognition in individuals with poor memories (Kaplan et al., 2000). A Swiss study determined that carbohydrate ingestion resulted in relatively better short-term memory and accuracy of tasks concomitant with higher metabolic activation. This finding supports the concept that good and stable cognitive performance is related to a balanced glucose metabolism activation state (Fischer et al., 2001). In addition, Nabb and Benton (2006) found that a greater intake of carbohydrates resulted in faster responses later in the morning after a high-carbohydrate breakfast, using the Hick Paradigm reaction time response test. However, the varying results reveal the need for continuing research in this important area. Links between food and behavior are complex, and the relationship between diet and possible changes in cognitive performance need further investigation so that practical advice can be given to populations such as pilots whose performance is critical to air safety.

CONCLUSIONS

Aircrew and pilot human factors issues (diet, nutrition, and health of the pilot) help contribute to and in part account for up to 91% of general aviation accidents and 78% of aircraft carrier accidents today (National Transportation Safety Board, 2009a, 2009b; Shappel and Wiegmann, 2004). Focusing on specific human issues such as diet and its relationship to flight performance could help reduce the rate of pilot errors and accidents and warrants further exploratory research. Some published reports support the findings of this study, whereas others contradict them. Our findings, that pilots consuming high-fat and high-carbohydrate diets have better cognitive flight performance scores than pilots consuming high-protein diets, can have consequences for the workplace.

Impact and Implications: So What?

Pilot performance scores were significantly poorer for participants consuming high-protein diets as compared to high-fat and high-carbohydrate diets. Results of this study have broad implications because peak performance of pilots is critical in today’s complex environment. Thus, knowledge of the effects of diet on flight performance has practical ramifications for pilots in combat situations as well as for general aviation and commercial pilots.

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TABLE 1

Characteristics of the Commercial Pilots in the Study

Variable	**M**	**SD**
Demographics		
Age (years)	20.80	1.90
Education (years)	13.80	1.00
Flight time (total hours)	146.60	38.60
Instrument time (total hours)	45.50	39.50
Health status		
Body mass index (BMI)	24.80	3.50
Sleep index (scores)	92.18	4.26
Activity levels (score)	269.61	176.16
Anxiety (Zung’s Self-Rating Anxiety Scale)		
Anxiety (score)	36.64	6.71
Environmental factors		
Cockpit noise (decimeter level)	75.40	4.30
Cockpit temperature (degrees Fahrenheit)	74.67	1.64

Note. $N = 45$.

TABLE 2

Repeated-Measures Analysis of Variance of Mean Flight Performance Deviation Scores

	Raw Data		SQRT Data		
Variable	**M**	**SD**	**M**	**SD**	**F**
Airspeed					
Control diet	9.6	3.1	3.1	.5	> 1.5
Fat diet	10.8	3.8	3.2	.6	
Protein diet	10.4	3.0	3.2	.5	
CHO diet	10.1	2.8	3.1	.4	
Altitude					
Control diet	172.6	124.1	12.7^{1}	3.4	$> 5.7^{**}$
Fat diet	150.8	85.4	11.9^{2}	3.1	
Protein diet	217.1	97.3	14.4	3.0	
CHO diet	169.2	83.1	12.7^{3}	3.1	
Heading					
Control diet	35.3	36.2	5.4	2.5	$> 3.2^{*}$
Fat diet	28.9	4.0	5.3	1.0	
Protein diet	23.4	20.3	4.5^{4}	1.8	
CHO diet	26.9	21.1	4.8	1.9	
Overall flight performance					
Control diet	217.5	135.9	14.3	3.5	$> 3.08^{*}$
Fat diet	198.2	100.3	13.7^{5}	3.2	
Protein diet	250.9	109.8	15.5	3.1	
CHO diet	206.1	97.6	14.0^{6}	3.3	

Note. n = 43. Post-hoc Fisher's least significant difference test; SQRT = square root transformation; CHO = Carbohydrate.

[*] $p \leq .05$.

[**] $p \leq .01$.

1, 3, 4, 5, 6 $^{***}p \leq .001^{2}$.