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Research report

Low-carbohydrate weight-loss diets. Effects on cognition and mood

Kristen E. D'Anci [a,b], Kara L. Watts [a], Robin B. Kanarek [a], Holly A. Taylor [a,*]

[a] Department of Psychology, Tufts University, Medford, MA 02148, United States
[b] Jean Mayer USDA Human Nutrition Research Center on Aging, United States

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ABSTRACT

To examine how a low-carbohydrate diet affects cognitive performance, women participated in one of two weight-loss diet regimens. Participants self-selected a low-carbohydrate ($n = 9$) or a reduced-calorie balanced diet similar to that recommended by the American Dietetic Association (ADA diet) ($n = 10$). Seventy-two hours before beginning their diets and then 48 h, 1, 2, and 3 weeks after starting, participants completed a battery of cognitive tasks assessing visuospatial memory, vigilance attention, memory span, a food-related paired-associates a food Stroop, and the Profile of Moods Scale (POMS) to assess subjective mood. Results showed that during complete withdrawal of dietary carbohydrate, low-carbohydrate dieters performed worse on memory-based tasks than ADA dieters. These impairments were ameliorated after reintroduction of carbohydrates. Low-carbohydrate dieters reported less confusion (POMS) and responded faster during an attention vigilance task (CPT) than ADA dieters. Hunger ratings did not differ between the two diet conditions. The present data show memory impairments during low-carbohydrate diets at a point when available glycogen stores would be at their lowest. A commonly held explanation based on preoccupation with food would not account for these findings. The results also suggest better vigilance attention and reduced self-reported confusion while on the low-carbohydrate diet, although not tied to a specific time point during the diet. Taken together the results suggest that weight-loss diet regimens differentially impact cognitive behavior.

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Many people cannot resist the promises of low-carbohydrate diets, including promises of quick weight loss while consuming high-protein, high-fat foods and "dieting without hunger." As such, low-carbohydrate diets have gained in popularity. With their popularity come questions about how such diets may affect individuals, beyond just weight loss (Bray, 2003). While carbohydrate consumption appears to improve cognitive and physical performance (Benton, 2002; Benton, Brett, & Brain, 1987; Benton, Slater, & Donohoe, 2001; Busch, Taylor, Kanarek, & Holcomb, 2002; Gonder-Frederick et al., 1987; Hall, Gonder-Frederick, Chewning, Silveira, & Gold, 1989; Kanarek & Swinney, 1990; Messier, Desrochers, & Gagnon, 1999; Welsh, Davis, Burke, & Williams, 2002) and being on a weight-loss diet can impair cognitive ability (Bryan & Tiggemann, 2001; Green & Rogers, 1998; Kemps & Tiggemann, 2005; Kemps, Tiggemann, & Marshall, 2005; Shaw & Tiggemann, 2004; Vreugdenburg, Bryan, & Kemps, 2003), few published studies have examined how it affects cognitive performance. Weight-loss diets and calorie restriction globally affect cognitive performance with dieters showing impairments in central executive function and increased interference from preoccupying thoughts related to food relative to non-dieters (Green & Rogers, 1998; Kemps et al., 2005; Shaw & Tiggemann, 2004). Recent research suggests that cognitive deficits may result from long-term adherence to low-carbohydrate diets. For obese people, following a low-carbohydrate, high-fat diet for 8 weeks was associated with impairments in cognitive processing speed, but not in working memory relative to those following a more traditional high-carbohydrate, low-fat regime (Halyburton et al., 2007). Given the current popularity of low-carbohydrate diets and current knowledge of how acute dietary intake affects cognition, it is important to more fully investigate how these diets influence cognitive performance.

Glucose is the brain's primary fuel, but it is not stored in the brain (Morris & Saril, 2001; Sieber & Trastman, 1992; Wenk, 1989). All digestible carbohydrates are ultimately broken down into monosaccharides, primarily glucose. After absorption from the gastrointestinal tract, glucose is carried in the blood stream to the liver, brain and other tissues. Furthermore, the brain lacks enzymes that are present in the liver for converting amino acids and fats into glucose. As such, the brain is dependent on circulating blood glucose for fuel, and experiences consequences related to fluctuating blood glucose levels (McCall, 2002). Acute hypoglycemia

* Corresponding author.
E-mail address: holly.taylor@tufts.edu (H.A. Taylor).

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impairs cognitive function and interferes with selective cognitive processing (Brody, Keller, Degen, Cox, & Schächinger, 2004; Hvidberg et al., 1996; Schächinger, Cox, Linder, Brody, & Keller, 2003), indicating the importance of adequate blood glucose in brain function. Glucose is stored in limited quantities as glycogen in muscle and liver, and glycogen is converted back into glucose and released into the blood stream as needed. However, as the body does not have vast glycogen stores, a continual dietary source of carbohydrates must replenish these stores. The body will consume its glycogen stores in a matter of 1–2 days. Low-carbohydrate diets, particularly in the initial introductory phase, contain little or no carbohydrate—restricting intake to below 20 g/day. For comparison, the recommended daily allowance (RDA) for carbohydrate is 130 g/day based on the average minimum amount utilized by the brain (FNB & IOM, 2002).

In the absence of dietary carbohydrate and upon depletion of glycogen stores, the body will begin to metabolize body fat into ketone bodies, which can then be used, albeit less efficiently, by the brain and body as fuel. Lipolysis though ketosis is the lynchpin of low-carbohydrate weight loss, and is actively encouraged in some low-carbohydrate programs. The fact that ketogenic diets are used medically to manage epilepsy and seizures suggests that they can profoundly influence brain functioning (Cantello et al., 2007; Freitas, da Paz, Casella, & Marques-Dias, 2007; Hartman, Gasior, Vining, & Rogawski, 2007). Research in young animals shows that ketogenic diets not only can slow seizure activity, but also results in reduced brain growth and impairment in visuospatial tasks (Zhao, Stafstrom, Fu, Hu, & Holmes, 2004). It is plausible, therefore, to propose that very low carbohydrate diet plans may have long-term effects on cognitive functioning in individuals following such diets in comparison to individuals consuming adequate levels of carbohydrate.

The present study examined how the initial stages of two weight-reducing diets, a low-carbohydrate diet similar to the Atkins™ diet, and another with macronutrients proportions typically recommended by the American Dietetic Association (ADA), affect cognitive performance. Low-carbohydrate diets typically have a 2-week introductory period wherein people severely limit carbohydrates. After this point, carbohydrates are gradually reintroduced, but generally remain below the RDA. To mimic this pattern of restriction and reintroduction of dietary carbohydrate, participants followed a 3-week dietary regimen that included a 1-week period that eliminated carbohydrates. We proposed that dietary carbohydrate restriction would impair cognitive performance in the early phases of the diet, and that this impairment would be ameliorated by the reintroduction of carbohydrate.

Methods

Participants

Participants consisted of 19 women, aged 22–55 years, recruited from faculty and staff at Tufts University and from the surrounding community. To better ensure compliance with the diets, participants selected the diet plan they preferred, either the low-carbohydrate (LC diet) or a low-calorie, macronutrient balanced diet (ADA diet). Nine women selected the LC diet and 10 selected the ADA diet.

To determine health eligibility, each participant completed a health-screening questionnaire. Exclusion criteria included any history of depression or other psychopathological condition, heart disease, diabetes, gastric bypass surgery, or any medication (exception—birth-control pills). Participants received $200 compensation for completing the study.

Materials

Questionnaires and cognitive assessments were chosen based on previous research in our laboratory that showed differences in cognitive functioning following dietary manipulation (e.g. Busch et al., 2002; Mahoney, Taylor, & Kanarek, 2007; Mahoney, Taylor, Kanarek, & Samuel, 2005), and designed to include a wide range of cognitive domains including vigilance attention, long-term and short-term memory, and visuospatial learning and memory. Food Stroop and food paired-associated memory tasks were based other research examining cognitive interference and food preoccupation in dietary restriction and cognition (Johansson, Ghaderi, & Andersson, 2005).

Profile of Mood States (POMS) Questionnaire

The POMS is an inventory of subjective mood states (McNair, Lorr, & Droppleman, 1994) that includes a series of 65 mood-related adjectives. Participants rate these adjectives on a five-point scale, using the response set of "How are you feeling right now?" Previous research has shown that the adjectives factor into six mood subscales: tension, depression, anger, vigor, fatigue, and confusion.

Hunger questionnaire

This questionnaire includes questions designed to assess current hunger and uses 10-point Likert ratings (1 = not at all to 10 = severe). The scale was adapted from a questionnaire originally intended to assess thirst (Engell et al., 1987), however ratings were limited to embedded questions related to subjective feelings of hunger such as "My stomach is rumbling"; "My stomach aches"; and "I feel lightheaded".

Cognitive tasks

The study included five computer-based cognitive tasks assessing visuospatial memory, vigilance attention (CPT) with a concurrent secondary task, digit span (forward and backward), and both positive and negative consequences of food preoccupation. Participants completed these tasks on Macintosh computers running programs developed either in-house or using Superlab™ software.

The food Stroop task examined processing decrements as a function of food preoccupation. It consisted of 108 words, divided into three word types (good food, forbidden food, nonfood) presented in blue, green, red or orange font. There were equal proportions of word types and colors within word type. Good foods included such items as "apple" and "barley". Forbidden foods included items such as "beer" and "cupcakes", and nonfood items included material objects, such as "chair" and "car".

The food paired-associates memory task examined improved memory for food-related words, a presumed positive effect of food preoccupation. It included four types of word pairs: food–food, food–nonfood, nonfood–food, and nonfood–nonfood. Pairs appeared side-by-side in black font. There were five word-pair lists, each with six examples of every pair type, resulting in 24 pairs per list.

The visuospatial memory task used five fictitious maps, each containing 24 countries. Country names on each map fit a specific theme: bones, flowers, colors, gemstones, or metals. In other words, each country name for a particular map had a name consistent with the overall map theme. A blank outline of the map, printed on paper, was used for recall.

Vigilance attention was assessed using a visual continuous performance task (CPT) with both primary and secondary components. For the primary component, a computer program presented letters, one at a time, with designated target letter combination (e.g., XB). Letters appeared for 333 ms with an ISI of 750 ms. Three versions of the task involved different target letter combinations: XB, TG, and PR. Target combinations appeared 25% of the time and false positives (one letter from the target pair) appeared 25% of the time. The secondary component involved an audiotape with a sequence of beeps, presented in the left or right channel, at a rate of 1.5 s/beep, and duration of 0.5 s/beep. The target sequence involved three beeps in the left channel. The full recording contained 80 target sequences within a 650-beep list. We constructed the list based on the following restrictions: at least one and no more than five beeps could occur between target sequences and no more than two right-channel beeps could occur in a row. The target sequence occurred approximately 12% of the time.

Design and procedure

The overall experiment design involved a 2 (diet: low-carb, ADA) $\times$ 4 (test session) repeated measures mixed-factor design. Since participants self-selected diets, the baseline testing session was included to examine a priori diet group differences and to provide practice on the tasks.

Upon enrollment, participants chose either the LC or the ADA diet—a macronutrient nutritionally balanced diet, akin to the 2005 American Dietetic Association guidelines diet. After selecting a diet, the investigator thoroughly reviewed the diet guidelines and discussed the nature of the study with the participant. Individuals who selected the LC diet received instructions to reduce their daily carbohydrate intake to 0 g for 1 week. For the second week, they could add between 5 and 8 g of carbohydrates per day. For the third week, they could add an additional 5–8 g per day (total 10–16 g per day). Individuals who selected the ADA diet calculated their recommended caloric intake per day based on their current weight. Then, a list based on the ADA Food Exchange List (NHLBI Web site, most recently accessed on 14/8/2007) was reviewed and given to participants. All participants, regardless of diet, received a food journal and instructions to maintain a strict record of every food and beverage consumed over the course of the study. In addition, they were asked to avoid any food or beverage labeled as having "net carb" values, as these products were not standardized by the FDA for carbohydrate value at the time of the study. Participants continued on their selected diet for 3 weeks.

Participants completed five testing sessions during the afternoon and early evening hours (3:00–7:00 pm) and each participant came at the same time each session. The baseline session occurred before the start of the diet. The first two test sessions occurred during the first week of the diet (48 h and 1 week after starting), followed by one session during each of the following 2 weeks. The first two sessions were scheduled to maximize detection of cognitive changes due to depletion of glycogen stores during the LC diet. The test session during the second week was designed to capture cognitive performance after reintroduction of minimal carbohydrates.

All test sessions followed the same procedures. Participants began by weighing in. At this point their food journals were reviewed by the researcher, who was not blinded to condition, to ensure diet compliance and to answer any diet-related questions (at the baseline session, participants were given dietary guidelines and instructed how to complete the food journals). Then, participants completed the POMS and the hunger/thirst questionnaires followed by the computerized cognitive task battery. Participants completed the cognitive tasks in a counterbalanced order. Since self-perceived performance on cognitive tasks can influence mood, the POMS was administered prior to cognitive testing.

During the food Stroop task, participants saw the colored words on the screen one at a time and responded by designating the color of the word using keys marked with corresponding colored squares as quickly and as accurately as possible. Words were randomized across participants. Dependent measures included accuracy and response time as a function of word type.

During the food paired associates memory task, participants first read instructions stating that they would view word pairs and then receive a cued recall test. During viewing, participants saw a list of 24 word pairs. Each pair appeared on the screen for 2500 ms followed by a 1500 ms ISI. For the cued recall, participants received a list, on paper, that included the first word in every pair. They had 4 min to fill in the second word for all of the pairs. Number of correct, incorrect, and blank items served as dependent measures.

For the digit span task, participants viewed brief presentations of random strings of digits (0–9), beginning with two digits, and then recalled the string by typing them. The number of digits per string increased after correct recall. The digits were presented for a base duration of 1000 ms and duration increased by 200 ms for each additional digit. There were two versions of this task. For forward digit span, participants recalled digits in the order presented. For backward digit span, they recalled digits in reverse order. If participants erred during recall, they received a second string of the same length. Errors on two consecutive trials of the same string length ended the task. The number of digits in the longest string correctly recalled served as the dependent measure.

For the visuospatial memory task, participants were to learn one of the theme maps. They first viewed an outline map of all the countries on the computer screen and then country names appeared one at a time for 4000 ms each. During this viewing phase, each name was presented twice in the same order. After viewing the map, participants received the blank paper outline map and had 5 min to fill in as many countries as they could. Participants also completed long-term map recall at the beginning of the next testing session. Long-term recall was not collected for the third week test session. Dependent measures for this task included the number of correctly and incorrectly recalled countries as well as the number of countries left blank.

The visual CPT task, with its accompanying secondary task, lasted 15 min. During the time, participants monitored the computer screen for presentation of the target letter combination and listened to the secondary task audiotape through stereo headphones attached to a tape player. For the primary task, when they saw the target letter combination, they pressed the spacebar. To ensure they attended to the secondary task, they had to write a tick-mark on a piece of paper after hearing three consecutive beeps in their left ear. Dependent measures for the primary task included hit rate, false alarm rate, miss rate, and response time to hits.

Data analysis

Data were analyzed using SPSS 12.0 for Windows. For all tasks a preliminary two-tailed, independent samples *t*-test evaluated baseline differences between diet groups. This baseline analysis is critical for the overall interpretation of the findings, as any baseline differences were subsequently accounted for by normalizing performance to baseline, and are described within the context of results for individual tasks. All analyses included diet as a between-groups factor and test session as a within-groups factor. Other factors specific to tasks will be discussed in context of results of individual tasks. Alpha was set at 0.05.

Results

Participants

The initial BMI of the experimental groups did not vary at the beginning of the study (LC diet $M = 28.1$ kg/m^2; ADA diet

$M = 30.1\ kg/m^2$; range: 22–43.7 kg/m^2), and weight loss was not significantly different over the 3-week experimental period, weight loss was less than 2 kg in each group (LC diet $M = 1.88$ kg; ADA diet $M = 1.76$ kg; n.s.). In checking the food diaries, the LC group was 93.3% in compliance with diet guidelines and carbohydrate limits, and the ADA group was 90.5% in compliance with diet guidelines. Food items listed in food diaries were compared to the list of guidelines for each diet. Non-compliance was noted as intake of carbohydrate in the LD diet or exceeding dietary exchanges for the ADA diet, and the participant was reminded of respective dietary guidelines. Subjective hunger ratings did not differ between the two diet conditions at any time point.

Food Stroop

Preliminary analyses indicated no response differences to *good* and *forbidden food* words. Thus, responses to these two word types were collapsed and comparisons made between *food* words and *nonfood* words. Baseline analyses of average reaction time, broken down by word type (*food* or *nonfood*), showed no effect of diet group ($t(17) = -1.15$, $p > .25$) for *nonfood* words or for *food* words ($t(17) = -1.99$, $p > .05$).

The design analysis for the food Stroop involved a 2 (diet: low-carb, ADA) × 4 (test session: 48 h, 1 week, 2 weeks, 3 weeks) × 2 (word type: food, nonfood) mixed factorial ANOVA. Results indicated faster responses to *nonfood* ($M = 836$ ms) than to *food* words ($M = 851$ ms), ($F(1, 17) = 8.219$, $p < .05$). Average reaction time also decreased across sessions ($F(3, 51) = 9.243$, $p < .001$) indicating a practice effect ($M = 885$ ms for 48-h session, 843 ms for 1-week session, 835 ms for 2-week session, and 809 ms for 3-week session). Qualifying these main effects was a diet by word type interaction, ($F(1, 17) = 5.092$, $p < .05$). Participants on the ADA diet responded faster to *nonfood* words, but those on the LC diet showed little difference as a function of word type (see Fig. 1). Results also showed a three-way interaction between diet and test session and word type, ($F(3,51) = 3.126$, $p < .05$; see Fig. 2). Over all test sessions, participants on the ADA diet showed a practice effect (session effect, $F(3, 27) = 12.456$, $p < .001$) and consistently responded faster to nonfood words (word type effect, $F(1, 9) = 20.169$, $p < .005$). In contrast, LC participants' response times did not show the consistent practice effect, as seen in slower responses for 2-week session, relative to 1-week session and did not consistently respond faster to nonfood words (session by word type interaction, $F(3, 24) = 4.206$, $p < .05$). Although accuracy data was collected, it was not analyzed due to overall high accuracy rates.

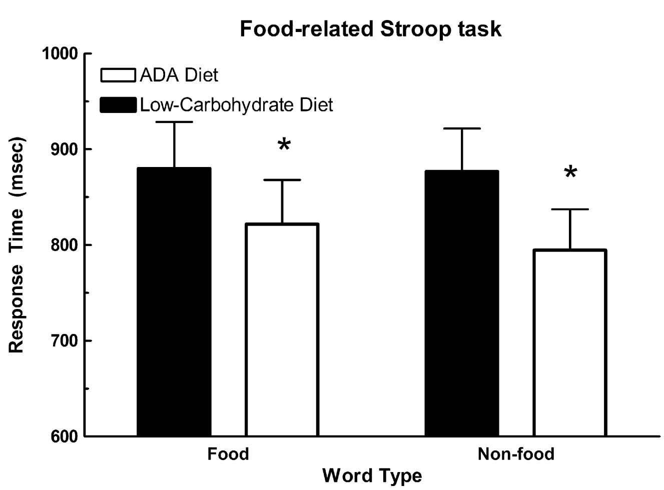

Fig. 1. Reaction time (ms: mean + SEM) in the food-related Stroop task. Participants in the low-carbohydrate group had slower reaction times regardless of word type than did participants in the ADA-recommended diet condition.

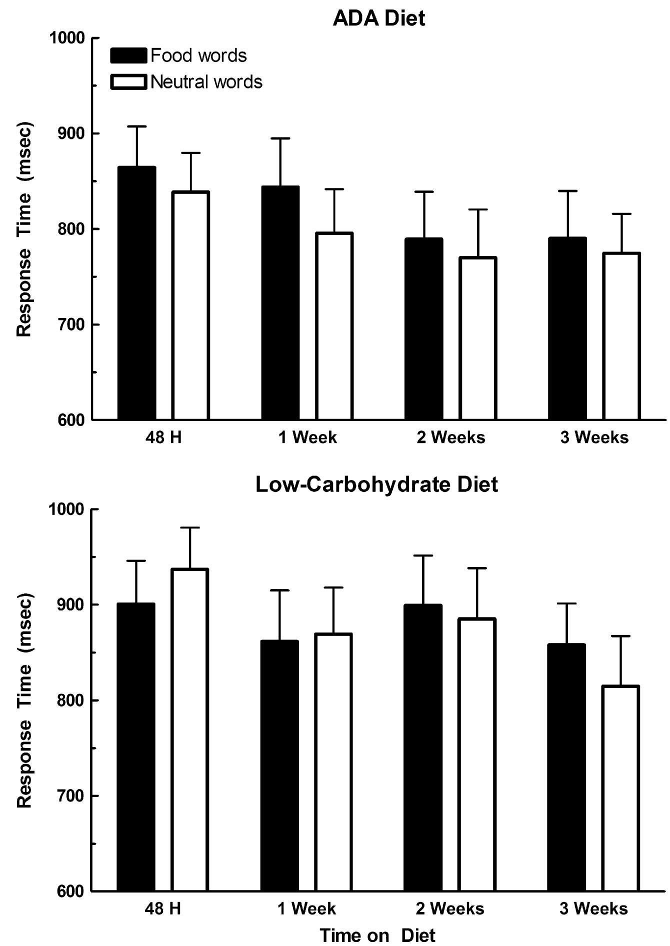

Fig. 2. Response times (ms: mean + SEM) in the ADA diet decreased over the 3 weeks on the diets, with overall faster responses to neutral words (top panel). Reaction time of low-carbohydrate participants increased for week 2 relative to week 1, and showed a larger increase for food compared to neutral words (bottom panel).

Food paired-associates

The baseline analyses of correct, incorrect, and blank responses revealed no diet group differences. The analysis consisted of 2 (diet: low-carb, ADA) × 4 (test session: 48 h, 1 week, 2 weeks, 3 weeks) × 4 (pair type: food–food, food–nonfood, nonfood–food, nonfood–nonfood) mixed-factor repeated measures ANOVA. Results of correct responses showed an effect of pair type ($F(3, 51) = 6.421$, $p < .005$). *Post hoc* comparisons indicated fewer correct responses to mixed pairs (food and nonfood, regardless of order) compared to nonfood–nonfood pairs ($ps < .05$), but no difference between food–food and nonfood–nonfood pairs. Analysis of blank responses mirrored that of correct ones, with an effect of pair type ($F(3, 51) = 8.187$, $p < .005$). *Post hoc* comparisons indicated more items left blank with mixed pairs (regardless of order) compared to nonfood–nonfood pairs ($ps < .01$), but no difference between food–food and nonfood–nonfood pairs. None of the measures showed either a main effect of or any interactions with diet.

Digit span (forward and reverse)

The baseline analysis showed no diet group differences for digits recalled in either order. Analyses showed no significant

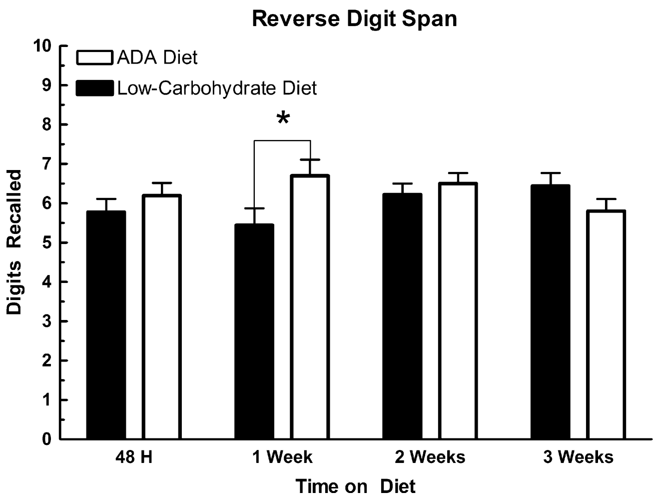

Fig. 3. Performance on the reverse digit span was significantly worse for participants in the low-carbohydrate condition after 1 week on the diets relative to the ADA diet (mean number correct + SEM). Performance at other time points did not vary as a function of diet.

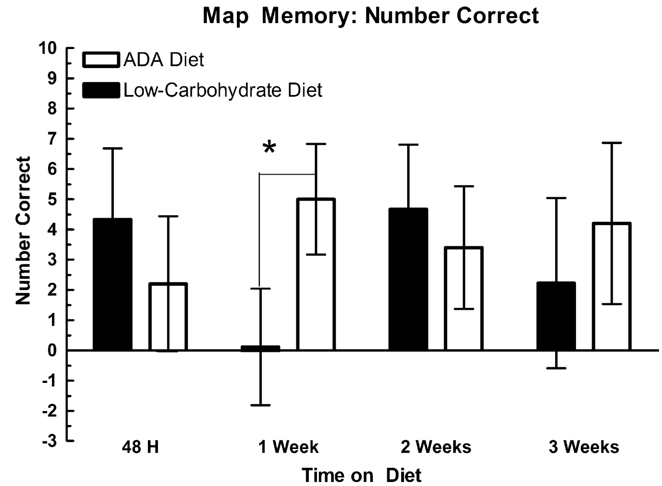

Fig. 4. Correct placement of item in the short-term map recall task (mean + SEM). Participants in the low-carbohydrate condition correctly placed significantly fewer items after 1 week on the diets relative to those in the ADA condition. Performance at other time points did not vary as a function of diet. *Note*: data are normalized to baseline performance.

effects on forward recall. Reverse recall performance showed interaction between diet and test session ($F(3, 51) = 2.87$, $p < .05$) (see Fig. 3). Follow-up two-tailed, independent sample *t*-tests showed that diet group differences occurred only for the 1-week session, i.e. at the point of greatest glycogen store depletion ($t(17) = 2.12$, $p < .05$). ADA dieters recalled more digits than LC dieters. No other main effects or interactions reached significance.

Visuospatial map task

Dependent measures included numbers of correctly placed, incorrectly placed, made-up (i.e., not on original map), and blank items for both short-term and long-term recall. For short-term recall, baseline analysis indicated diet group differences for correctly placed and blank items (correct recall, $t(17) = -2.12$, $p < .05$, with LC ($M = 11.6$) participants correctly placing more items than ADA participants ($M = 7.8$); blanks, $t(17) = 2.36$, $p < .05$, and with LC ($M = 7.89$) participants leaving fewer blanks than ADA ($M = 12.5$) participants. To account for this baseline difference, subsequent analyses used normalized values, computed by subtracting each session score from the baseline score, resulting in a change score from baseline.

For short-term recall, there was an interaction between diet and test session for number of correctly placed items ($F(3, 51) = 2.694$, $p = .056$). This interaction showed diet-related differences only at the 1-week session, when glycogen store depletion is greatest (see Fig. 4). In this session, LC dieters correctly placed fewer items than did ADA dieters. No other short-term recall measure showed any effects.

For long-term recall, analysis of baseline performance showed diet group differences for number of incorrectly placed ($t(17) = -4.61$, $p < .01$), and blank items ($t(17) = 3.83$, $p < .005$) LC participants placed more items incorrectly ($M = 6.33$) on average than ADA participants ($M = 1.4$), but had fewer blank items ($M = 13.6$) than ADA participants ($M = 20.1$). These baseline differences warranted calculation of normalized values.

The long-term memory analysis revealed a diet by session interaction for made-up items ($F(2, 32) = 4.597$, $p < .05$, $MSe = 0.512$; see Fig. 5). Across sessions, LC participants included increasingly more made-up items while ADA participants showed little change across the sessions.

CPT

Since the CPT measures vigilance attention, analyses divided the total task time into three equal 5-min intervals so as to examine performance as a function of time on task. Thus, analyses consisted of a 2 (diet: low-carb, ADA) × 4 (test session: 48 h, 1 week, 2 weeks, 3 weeks) × 3 (test interval: beginning, middle, end) mixed-factor repeated measures ANOVA. Analyses were conducted on hit, miss, and false alarm rates as well as response time to hits. No baseline differences between diet groups appeared in preliminary analyses for any of the dependent measures.

For hit rate, the analysis showed main effects of test session ($F(3, 51) = 4.729$, $p < .01$, $MSe = 60.58$), and test interval ($F(2, 34) = 4.104$, $p < .05$, $MSe = 17.1$), but no diet-based effects. For test session, hit rate generally improved across sessions with participants having more hits during the 2-week and 3-week sessions relative to the 48-h session ($ps < .05$). For test interval, hit rate generally improved as a session went on with participants having more hits during the middle and end 5-min interval relative to the beginning ($ps < .05$).

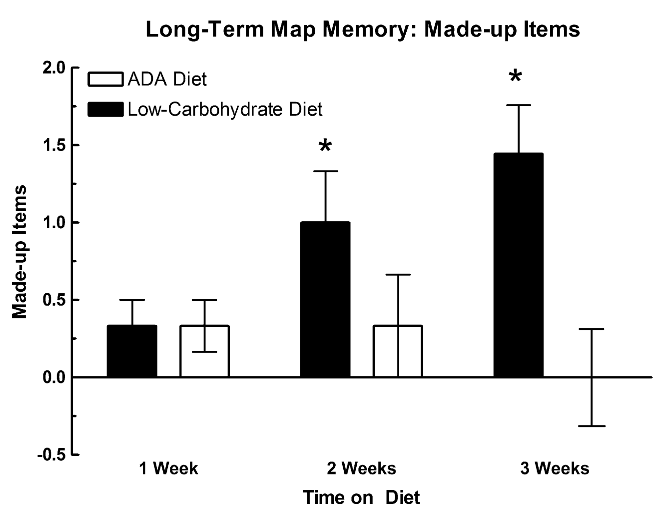

Fig. 5. Number of made-up locations in the long-term map recall task (mean + SEM). Across over the 3 weeks on the diets, low-carbohydrate participants included increasingly more made-up items while ADA participants showed little change over time. *Note*: data are normalized to baseline performance.

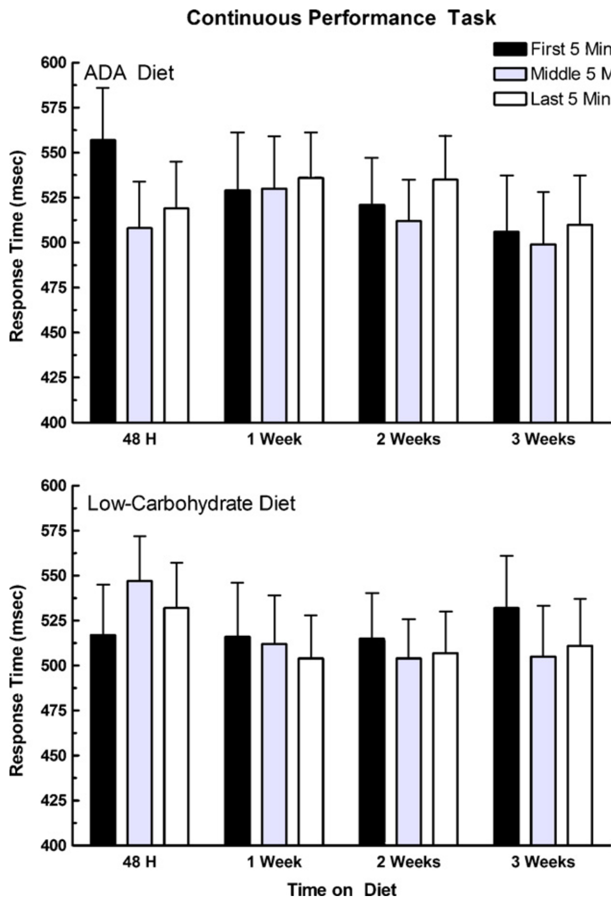

Fig. 6. Response time (ms: mean + SEM) for correct responses in the visual continuous performance task across all weeks. Within each session, for the middle and final test intervals, response time increased for ADA participants (top panel) and decreased for low-carbohydrate participants (bottom panel).

For response time to hits, the analysis showed a diet by session by test interval interaction ($F(6, 102) = 3.465$, $p < .005$, $MSe = .0008$). The main point of interest in this interaction is that for middle and end time intervals, response time decreased for LC participants and increased for ADA participants (see Fig. 6).

For misses, the analysis showed a main effect of test session ($F(3, 51) = 5.107$, $p < .005$, $MSe = 39.11$), and like hit rate, no diet effects. Participants had fewer misses in the 3-week session relative to the 48-h session ($p < .01$). For false alarms, the analysis also showed an effect of test session ($F(3, 51) = 3.306$, $p < .05$, $MSe = 13.27$), and no diet effects. Participants had fewer false alarms in the 3-week session relative to the 48-h session ($p < .05$).

POMS

Mood states addressed in the POMS questionnaire included vigor, anger, fatigue, depression, tension, and confusion factors. Only one factor showed any effects: confusion. Confusion scores showed an interaction between diet and session ($F(3, 51) = 3.664$, $p < .05$). This interaction suggests that the two diet groups reported similar confusion rates for the 48-h and 3-week test sessions, but that ADA dieters reported higher confusion for the 1-week and 2-week sessions (see Fig. 7).

Discussion

In the present experiment, cognitive effects of a low-carbohydrate diet were compared to those of another popular weight reduction diet over a 3-week period. Although weight loss was not our primary focus for this short-term experiment, both groups had small amounts of weight loss (<2.0 kg). Hunger ratings did not vary between the two diet conditions and only one select mood difference, confusion, appeared related to diet differences with ADA dieters reporting higher confusion ratings during the middle portion of the study.

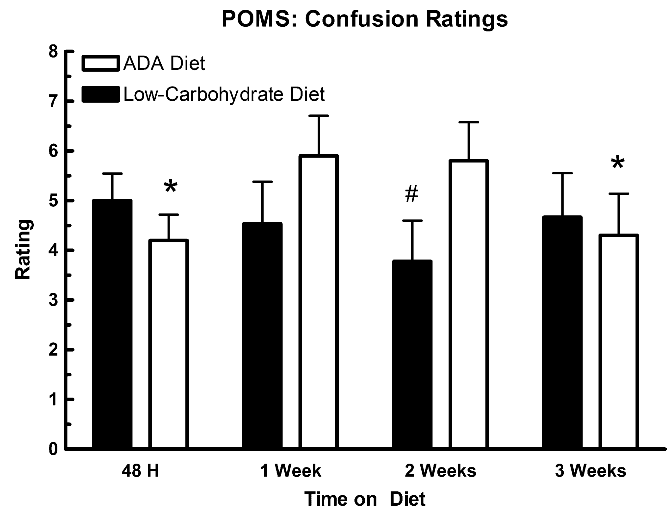

Fig. 7. POMS ratings for the confusion subscale across all weeks (mean + SEM). # indicates confusion ratings significantly lower at week 2 relative to week 1 for low-carbohydrate participants. * indicates that ADA participants reported higher confusion ratings for weeks 1 and 2 relative to the first 48 h and the last week.

In assessing cognitive performance, the test session 1 week after initiating the diets was of most interest because at this point there was little or no carbohydrate intake and glycogen stores should have been utilized. In this session, LC dieters showed decrements on two memory-related cognitive tasks. Short-term memory as assessed by the Reverse Digit Span task was impaired relative to ADA dieters. Performance on the less cognitively demanding Forward Digit Span was not affected. For map-recall, LC participants correctly placed fewer items during short-term recall. Long-term recall for information learned during session 2 showed LC dieters making more incorrect placements, and making up more names, but leaving fewer items blank. Remember that long-term recall occurred at the subsequent test session, i.e. at a point when low levels of carbohydrate had been reintroduced, suggesting that carbohydrate restriction contributed to memory encoding impairments that subsequently impacted both short and long-term recall. These data suggest that after a week of severe carbohydrate restriction, memory performance, particularly on difficult tasks (e.g., backward compared to forward digit span; spatial memory), is impaired.

The vigilance attention task (CPT), in contrast, showed a positive effect of the LC diet, compared to the ADA diet that was not linked to a specific test session. LC dieters responded faster to targets, particularly as the task progressed through its 15-min duration, suggesting better sustained attention. Other research has shown that eating meals high in protein (Lowden et al., 2004; Paz & Berry, 1997) or fat (Love, Watters, & Chang, 2005; Lowden et al., 2004) in the short term reduces fatigue and improves tasks requiring vigilance attention relative to meals high in carbohydrate. The present data suggest that longer-term adherence to a low-carbohydrate, high-protein/high-fat diet may have similar effects on attention.

Previous research by us and others has shown that acute intake of simple carbohydrates can improve performance on high-load cognitive tasks, but that simpler tasks are affected to a lesser degree, possibly representing a ceiling effect where simple task performance cannot be improved (for a review see D'Anci & Kanarek, 2006). Messier et al. (1999) compared college students' word list memory after either ingesting a glucose-containing or a saccharin-containing solution. Participants that ingested the glucose solution had higher recall rates. Similar findings have been seen on other cognitive tasks, such as short-term memory (Benton & Owens, 1993; Gonder-Frederick et al., 1987, Hall et al., 1989; Martin & Benton, 1999), the rapid information processing task, the Stroop task, word recall (Benton, Owens, & Parker, 1994), reaction to frustration, and the ability to sustain attention (Benton et al., 1987).

In research comparing the effects of a high-fat, low-carbohydrate diet and a high-carbohydrate, low-fat diet, Halyburton et al. (2007) found that working memory, as measured by the reverse digit span, was not affected by diet. In contrast, performance on a speed of processing task showed less improvement over time in the low- relative to the high-carbohydrate condition. In the present study, participants consuming very little to no carbohydrates showed spatial memory and reverse-digit span decrements that were reversed when carbohydrate intake was resumed. There are a number of differences between the Halyburton study and the present research which could account for the different results in cognition and mood. The most relevant factors would be that in the former study, participants were fed planned diets for 8 weeks, whereas in our study participants chose their daily diets and followed particular diet guidelines for only 3 weeks, with carbohydrate intake increasing over the 3-week period. It was our goal in the present study to approximate what individuals following weight-loss diets would do during real-world conditions, and as such, our specific hypothesis and design focused on the early stages of following a restricted carbohydrate diet.

Diets high in protein are reported as being more satiating than other macronutrient components (Bertenshaw, Lluch, & Yeomans, 2008; Poppitt, McCormack, & Buffenstein, 1998), and the promise of many low-carbohydrate diets is "slimming without hunger." However, in this study, subjective hunger ratings were the same for both dietary conditions. Further, perception of hunger is also related to increased distracting thoughts about food. The present study provided no indication that differential pre-occupation with food contributed to the cognitive decrements. Performance on two tasks designed to address cognitive interference brought about by food pre-occupation (food-Stroop and food paired associates tasks) showed no effects of diet condition. While dieters tend to display pre-occupation with food relative to non-dieters (Kemps & Tiggemann, 2005; Kemps et al., 2005), all participants in our study were dieters. The present study provided no indication that the macronutrient composition of the diet produced differences in preoccupation with food. Taken together, these results suggest that changes in cognitive performance related to these two different weight reduction diets cannot be explained by either mental preoccupation with food or distraction by physiological signs of hunger.

In addition to cognition, mood has been reported to vary with weight-loss diets, either positive (Bryan & Tiggemann, 2001; Halyburton et al., 2007), possibly relating to mood improvements following weight loss, or negative (Burley, Kreitzman, Hill, & Blundell, 1992), relating to the negative signs of calorie-restriction. Mood is affected acutely by meal intake and meal composition, with meals high in carbohydrate tending to produce less alertness and more fatigue/sleepiness, and less tension/more calmness than meals high in protein (Paz & Berry, 1997; Smith, Leekam, Ralph, & McNeill, 1988; Spring, Maller, Wurtman, Digman, & Cozolino, 1982–1983). The present study found no compelling findings with respect to mood. Confusion was higher for the ADA diet condition relative to the LC condition, but no other mood differences were observed.

This study's strength is the inclusion of a broad range of cognitive tasks, designed to assess different domains of cognitive performance. Based on other research examining meal intake and cognitive performance, is it not surprising that different aspects of cognition (e.g. memory vs. attention) were affected differently by the two weight-loss diets. In other research in our laboratory, intake of confectionary snacks improved performance on an attention task, but memory was not affected (Busch et al., 2002). In related research, breakfast intake significantly improved short-term memory, visuospatial processing, and auditory attention, but not visual attention (Mahoney et al., 2005).

It should be noted that the caloric restriction in the present study was relatively mild, the sample size was modest, and that participants were permitted to self-select into diet conditions—in part to increase the likelihood of compliance. Weight loss over the 3-week period was modest (less than 2.0 kg for each group) and within established guidelines for safe weight loss. Participants most likely selected into a diet best fit their eating habits, although this was not assessed. If so, the diet conditions may not have been sufficiently different from normal to produce much dysphoria or food preoccupation. Research using randomized assignment into conditions would address this issue, although may result in reduced diet compliance. Future studies would employ randomized assignment to dietary conditions, larger sample sizes, and the inclusion of men.

"Lose 30 pounds before the holidays," "drop a jean size in two weeks," and "7 days to a slimmer you" are phrases designed to lure the prospective dieter into adopting one of the multitude of diet plans over all the others. Low-carbohydrate diets have gained in popularity because they make promises of rapid weight loss while continuing to eat often-favored foods. Another common phrase may be an important reminder to these prospective dieters—*You Are What you Eat*. Increasingly research has focused on nutritional "side effects" on behavior, such as cognitive performance (Benton et al., 2001; Kanarek & Swinney, 1990; Mahoney et al., 2005, 2007; Papanikolaou, Palmer, Binns, Jenkins, & Greenwood, 2006). The current study suggests that the macronutrient makeup of various weight-loss regimens are likely to have both positive and negative effects on our ability to think, attend, and remember.

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