Diet quality and cognitive function in an urban sample: findings from the Healthy Aging in Neighborhoods of Diversity across the Life Span (HANDLS) study

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Abstract

Objective: Poor diet quality contributes to morbidity, including poor brain health outcomes such as cognitive decline and dementia. African Americans and individuals living in poverty may be at greater risk for cognitive decrements from poor diet quality.
Design: Cross-sectional.
Setting: Baltimore, MD, USA.
Subjects: Participants were 2090 African Americans and Whites (57% female, mean age = 47·9 years) who completed two 24 h dietary recalls. We examined cognitive performance and potential interactions of diet quality with race and poverty status using baseline data from the Healthy Aging in Neighborhoods of Diversity across the Life Span (HANDLS) study. Healthy Eating Index-2010 (HEI-2010) scores were calculated and interpreted using federal guidelines. A neurocognitive test battery was administered to evaluate cognitive function over several domains.
Results: Linear regression analyses showed that lower HEI-2010 scores were associated with poorer verbal learning and memory ($P < 0·05$) after adjustment for covariates. Diet quality within the sample was poor. Significant interactions of HEI-2010 and poverty status (all $P < 0·05$) indicated that higher diet quality was associated with higher performance on tests of attention and cognitive flexibility, visuospatial ability and perceptual speed among those below the poverty line. No significant race interactions emerged. Higher diet quality was associated with better performance on two measures of verbal learning and memory, irrespective of race and poverty status.
Conclusions: Findings suggest that diet quality and cognitive function are likely related at the population level. Future research is needed to determine whether the association is clinically significant.

Optimal cognitive function is an important indicator of quality of life and necessary for independent living across the lifespan[1]. Multiple indices of poor health have been associated with decrements in cognitive function[2]. Health effects on interindividual variability in cognitive function have been documented across the lifespan and health-related decrements in cognitive function[3], as detected by sensitive neuropsychological tests, are apparent in some middle-aged or younger adults[4,5]. These early decrements to cognitive function may negatively impact later-life cognitive outcomes[3]. Poor health behaviours, such as unhealthy eating, are also associated with worse cognitive outcomes and promote the onset and progression of cognitive decline and dementia[6]. Among Americans, diet quality is strikingly poor, with only 3 to 4% of US adults meeting federal dietary guidelines[7]. Poor eating among the majority of US adults suggests that the implications of a diet and cognitive function link may be widespread.

Growing evidence suggests poor diet quality is associated with reduced cognitive function and cognitive

decline. For example, high intakes of saturated and *trans*-unsaturated fats are associated with cognitive decline and risk of dementia[6]. Other evidence suggests high energy intake and habitual sugar intake may be deleterious to cognitive function[8,9]. In contrast, high diet quality has been shown to protect or enhance cognitive function. In that regard, a high-quality diet such as the Mediterranean diet, characterized by high intakes of vegetables, fruit, legumes, nuts, cereals and monounsaturated fat (e.g. olive oil), and moderate to low intakes of dairy, meat, poultry, fish and alcohol, is protective against cognitive decline, cognitive impairment and dementia[10]. Other evidence suggests specific benefits of the Mediterranean diet for global cognition[11], verbal memory, verbal fluency[12] and visual memory performance[13]. Similarly, intake of vitamin E, an antioxidant, has been associated with enhanced verbal memory and verbal fluency performance and psychomotor speed among women[14].

Prior research suggests that diet quality, measured by either nutrient- or food-based indices, varies as a function of race[15]. For example, in several studies, African Americans report poorer diet quality than other racial/ethnic groups[16]. Poorer diet quality among African Americans as compared with other races is associated with lower levels of education and literacy[17], reduced access to and unavailability of healthful foods[18], and cultural differences in food preferences, including a propensity for consuming high-energy, fatty foods[19]. African Americans may also be more likely to engage in maladaptive eating behaviours to cope with psychosocial stress and perceived racism that are unique to their social experiences[20].

Individuals living in poverty tend to consume poorer diets due to socio-economic and environmental barriers to healthful food consumption[21]. Socio-economic disadvantage is consistently associated with lower consumption of fruits and vegetables and higher consumption of energy-dense foods[21]. Inversely, researchers have found that as income increases, fruit and vegetable consumption tends to increase, improving the healthfulness of dietary patterns[22]. There are several explanations for the inverse association between diet quality and socio-economic status (SES). For example, the economic stratification of neighbourhoods tends to segregate lower-SES and higher-SES individuals, creating very different environments for consumption[23]. Individuals in economically disadvantaged neighbourhoods often have limited access to retail outlets that offer healthful foods coupled with greater exposure to advertisements that promote unhealthful food options[18]. In addition, home food environments, including the structure of meals and food availability constrained by lesser resources, play a role in poor diet quality among individuals of low SES[24].

Given the documented associations between diet quality and cognitive function, identifying cognitive domains that may be affected, as well as the profiles of individuals most at risk for cognitive decrements related to poor diet quality, is imperative. Since diet quality tends to be poorer among African Americans and individuals living in poverty as compared with other groups, it is possible that diet confers a greater influence on cognitive function in these groups, making them particularly vulnerable to cognitive decline and dementia. The primary aim of the current study was to examine cross-sectional relationships of diet quality, measured with the Healthy Eating Index-2010 (HEI-2010), with several domains of cognitive function. A secondary aim was to examine whether relationships of diet quality with cognitive function vary by race and poverty status. To date, we are unaware of any studies that have examined these associations in a racially and socio-economically diverse sample of adults.

Methods

Data source

The Healthy Aging in Neighborhoods of Diversity Across the Life Span (HANDLS) study is a 20-year prospective longitudinal study examining health disparities among African American and White adults in thirteen urban neighbourhoods of Baltimore City, MD, USA. Participants include a fixed cohort of 3720 community-dwelling White and African American men and women, initially 30–64 years of age, who are above or below 125 % of the 2004 Department of Health and Human Services poverty guideline. Participants were sampled from the thirteen neighbourhoods using predetermined contiguous census tracts of an area probability sample. Stratified random sampling was intended to include a range of socio-economic levels in a four-way factorial cross for age (seven 5-year age groups), both sexes, race (White, African American) and SES. The HANDLS study is currently collecting wave 4 data; data collection began in 2004. Only wave 1 data, collected between 2004 and 2009, were analysed for the current cross-sectional study. Wave 1 occurred in two phases. In phase 1, residential households were identified within selected neighbourhoods. Field interviewers identified eligible candidates at doorstep interviews and invited participation in HANDLS. After signing informed consents, participants completed a household questionnaire and the first of two 24 h dietary recall surveys. Trained professionals working in mobile research vehicles collected the comprehensive data for phase 2. Measurements included the second dietary recall, a battery of cognitive and neuropsychological tests, and extensive medical history and physical examinations. The mobile research vehicles were located in selected neighbourhoods where participants resided.

Overall inclusion criteria for HANDLS were ages 30–64 years, ability to give informed consent, ability to perform at least five study measures and possession of a valid picture ID. Exclusion criteria included: (i) pregnancy; (ii) having received chemotherapy, radiation or biological

cancer treatment within the past 6 months; (iii) self-reported AIDS; and (iv) presence of uncontrolled blood pressure (>160/100 mmHg). For more detailed procedures see Evans *et al*.[25].

Participants

A total of 2801 participants completed both phases 1 and 2. Among these participants, eighty were excluded due to HIV infection, sixty were excluded due to a history of stroke, sixty-nine were excluded due to transient ischaemic attacks, thirty were excluded due to low vitamin B_{12} (<200 pg/ml) and folate levels (<3·0 mg/ml), 124 showed probable cognitive impairment as indicated by a Mini-Mental Status Examination score <20[26], and 348 additional participants were excluded due to at least one missing dietary recall between the two visits. These exclusions resulted in a final sample of 2090 participants for analysis.

Diet quality measures

Participants were asked to recall all the foods and beverages consumed during the previous 24 h by trained interviewers on two occasions: during phase 1 (in-home interview) and phase 2 (mobile research vehicle visit). Interviewers recorded dietary recalls using the validated US Department of Agriculture Automated Multiple Pass Method[27,28]. Measurement aids including the Food Model Booklet, spoons, cups and a ruler were used to assist the participant in estimating accurate quantities consumed[29]. Foods and beverages reported in the dietary recalls were coded with their own unique food codes by trained nutritional professionals using the Food and Nutrient Database for Dietary Studies (FNDDS) version 3.0[30].

The HEI-2010, a recognized measure of diet quality based on compliance with the US 2010 Dietary Guidelines for Americans (DGA), was used in the present study[31,32]. Compliance was measured according to recommendations for types and amounts of food to consume from two perspectives: adequacy and moderation. Adequacy components included Total Fruit, Whole Fruit, Total Vegetables, Greens and Beans, Whole Grains, Dairy, Total Protein Foods, Seafood and Plant Proteins, and Fatty Acids. Moderation components included Refined Grains, Sodium, and Empty Calories. Scoring used a density-based approach, based on g/4184 kJ (1000 kcal) or percentage of energy, with ratios for fatty acids. Standards for maximum scores employed the least-restrictive recommendations, among those that vary by sex, age or energy intake. Adequacy and moderation component scores are summed to create the HEI-2010 total score. A detailed description of the calculation of the HEI-2010 scores for participants in the HANDLS study can be found on the HANDLS website[33]. The maximum possible HEI-2010 total score is 100. A higher HEI-2010 score corresponds to higher diet quality and better compliance to the DGA 2010[31]. Thus,

adequacy components receive the maximum number of points when intakes are at the recommended level or higher. Inversely, moderation components receive the maximum number of points when intake levels are at the standard or lower[31]. To date there are no specific criteria for score interpretation by component. Overall, scores that are closer to 100 are optimal.

Cognitive measures

Verbal learning and memory

The California Verbal Learning Test-II (CVLT-II) assesses verbal learning and memory[34]. The standard format assesses immediate and delayed recall and recognition of two sixteen-word lists. Recall of list A consists of five trials. Recall of list B takes place after list A and allows one trial. Following list B, short-delay free recall and cued recall of list A are tested. After a 20 to 30 min delay, long-delay free recall, long-delay cued recall and yes/no-recognition attempts of list A conclude the test. Total recall of list A, short-delay free recall, long-delay free recall and learning slope performance were assessed.

Non-verbal memory

The Benton Visual Retention Test assesses visual memory, visual perception and visuoconstructional abilities as participants view ten designs and reproduce each design, as precisely as possible, from memory[35]. The test is untimed and scored by the examiner. Test–retest reliability ranges from 0·74 to 0·84[36].

Working memory

The Digit Span subscale of the Wechsler Adult Intelligence Scale – Third Edition consists of a forward and backward test of attention, working memory and concentration[37]. In both tests, seven pairs of random number sequences, of increasing length, are presented verbally at a rate of one per second. In Digits Forward, the subject repeats the same number sequence after the examiner. In Digits Backward the participant is asked to repeat the number sequence in reverse order. The test is discontinued when the subject fails both the forward and backward trial of any given sequence string. Digits Forward and Backward are measured by the number of correct trials.

Attention and cognitive flexibility

The Trail Making Test (TMT) measures attention, scanning and visuomotor tracking, and cognitive flexibility[38]. The TMT is administered in two parts that are timed, lasting 5 to 10 min. TMT A is administered first. Subjects draw lines to connect, in ascending order, numbered circles randomly arranged on a page[38]. In TMT B, subjects connect numbered and lettered circles, alternating between number and letter in ascending order by drawing connecting lines. Each test requires that the correct sequence be followed in order to correctly complete the test. Cognitive

task demands in TMT B are greater than in TMT A; slower performance in TMT A appears to underlie deficits in TMT B[38]. Scores reflect time taken to complete the tasks; thus, higher scores reflect poorer performance. The test–retest coefficient for TMT A and TMT B is 0·79 and 0·89, respectively.

Visuospatial ability

The Card Rotations Test assesses visuospatial ability by testing competence in visualizing differences in card shapes[39]. Ten rows of eight cards each are compared with a sample card shape to determine if each card is rotated or flipped over, compared with the sample. Two sets of ten card rows must be completed in 3 min each. The score is the number marked correctly minus those marked incorrectly[39].

Perceptual speed

The Identical Pictures Test, also from the ETS Kit of Factor-Referenced Cognitive Tests, assesses three components of visual perceptual speed: perceptual fluency, decision speed and immediate perceptual memory. In this timed test, sample objects are matched with an identical picture in the adjacent row of test objects[39]. The score is the number of correct answers, minus a fraction of the number of incorrect answers.

Semantic fluency

The Semantic Fluency Test is used to assess spontaneous generation of words that correspond to a specific category in a set amount of time[36]. In this case, participants are told to generate as many animals as possible within 60 s. Afterwards, the total number of unique animals named is summed to generate a categorical animal fluency score. Test–retest reliability for the Semantic Fluency Test is sound, with coefficients greater than 0·70[36].

Covariates

Covariates included sociodemographic variables, depressive symptoms, health behaviours/lifestyle factors, cardiovascular and anthropometric measures, and haemodynamic measures. Covariates were selected based on significant correlations with diet quality and/or cognitive function and typical inclusion in the relevant literature. Variables that were tested as potential covariates, but were unrelated to diet quality or cognitive performance, included past alcohol use, past and current illicit drug use, and total serum cholesterol.

Sociodemographic variables

Education was assessed as the total number of years of formal education. Race was dichotomized by self-identification as African American or White. Poverty status was dichotomized using the US Census Bureau poverty thresholds for 2004 based on income, size of family and

related children under age 18 years. Poverty status was determined at the doorstep by asking the number of people in the household and then inquiring whether the household income was greater or less than the threshold for that household size. Poverty status is hereafter referred to as 'below the poverty threshold' (<125 % of the poverty threshold) or 'above the poverty threshold' (≥125 % of the poverty threshold)[40].

Depressive symptoms

Depressive symptomatology was assessed with the Center for Epidemiologic Studies Depression Scale (CES-D), a depressive symptomatology scale designed for non-clinical populations[41].

Health behaviours/lifestyle factors

The smoking status variable was dichotomized as 0 = not current user (i.e. never tried, never used regularly or former users) and 1 = current user. Alcohol status was coded as 0 = not current user (i.e. never tried, never used regularly or used >6 months ago) or 1 = used within the past 6 months. Lastly, hard drug use, defined as the use of marijuana, cocaine or opiates, was coded as 0 = not current user or 1 = used in the past 6 months.

Cardiovascular and anthropometric measures

A diagnosis of diabetes was documented by a fasting glucose value ≥126 mg/dl, evidence of prescribed diabetic medication or a self-reported history of diabetes. Height and weight were obtained using calibrated equipment, and BMI was computed as the ratio of weight to height-squared (kg/m^2).

Haemodynamic measures

The standard brachial artery auscultation method, following a 5 min rest in a seated position, was implemented to assess systolic and diastolic blood pressure measurements (SBP and DBP, respectively). Measurements were obtained on each arm, with the arm at a 90° angle from the body with the palm facing upward, with an appropriate cuff size. Two SBP readings were averaged and two DBP readings were averaged to yield an estimate of participants' resting SBP and DBP. Since SBP and DBP are highly correlated, systolic hypertension is more common among older adults than diastolic hypertension, and our sample was more likely to have elevated SBP, not elevated DBP, only SBP was included in the regression analyses to avoid multicollinearity.

Statistical analyses

All analyses were computed using the statistical software package IBM SPSS Statistics Version 22.0. All variables were assessed for outliers, homoscedasticity and assumptions of normality. To determine relationships between diet quality and neurocognitive performance,

sequential linear regressions were run for each of the neurocognitive outcome variables with HEI-2010 score as the main predictor. All outcomes were analysed as continuous variables. Interaction terms were created to assess race and poverty status as effect modifiers. Variables were entered into the models in the following order: block 1 = age, race, sex, education, poverty status, CES-D score, current alcohol use (yes/no), current cigarette smoker (yes/no), BMI, mean SBP and diabetes status; block 2 = HEI-2010 score; and block 3 = HEI-2010 score × race interaction term and HEI-2010 score × poverty interaction term.

Results

Sample characteristics

Descriptive statistics for all demographic characteristics, covariates and cognitive measures are found in Table 1. The mean age of participants (*n* 2090) was 47·85 (SD 9·22) years. The sample was comprised of 51·2% African Americans and 42·8% males. Mean educational attainment was 12·16 (SD 2·89) years. Forty-two per cent of the sample fell below the poverty line. Mean BMI of 30·26 (SD 8·03) kg/m^2 was in the obese range. Mean SBP of 120·80 (SD 17·79) mmHg was at the lower limit of pre-hypertension,

and 16·5% had a diagnosis of diabetes. Self-reports of current illicit drug use, alcohol use and cigarette use were 5·9, 52·5 and 49·1%, respectively. HEI-2010 scores were approximately 43 out of 100, reflecting poor compliance with the DGA 2010 and thus poor diet quality. There were no significant differences in HEI-2010 scores by race or poverty status.

Sequential linear regression findings

Unadjusted associations between HEI-2010 scores and cognitive test scores are provided in Table 2. Prior to adjustment, HEI-2010 scores were significantly and positively correlated with CVLT-II list A recall and CVLT-II learning slope. Significant relationships of covariates (block 1), significant and non-significant main effects (block 2) and significant and non-significant interactions (block 3) are reported with respect to each cognitive outcome in Table 3. No significant race interactions emerged in any of the models.

Verbal learning and memory

After adjustment for all covariates that included age, race, sex, education, poverty status, CES-D score, current alcohol use (yes/no), current cigarette smoker (yes/no), BMI, mean SBP and diabetes status, HEI-2010 scores were significantly associated with CVLT-II list A recall

Table 1 Descriptive statistics for sample characteristics and cognitive test scores for the total sample and poverty status groups: White and African American men and women (*n* 2090) from urban neighbourhoods in Baltimore, MD, USA; Healthy Aging in Neighborhoods of Diversity across the Life Span (HANDLS) study

Characteristic/test score	Total sample (*n* 2090) Mean or %	SD	Below the poverty threshold (*n* 878) Mean or %	SD	Above the poverty threshold (*n* 1212) Mean or %	SD
Age (years)	47·85	9·22	47·10	9·00	48·39**	9·33
Education (years)	12·16	2·89	11·35	2·51	12·76***	3·00
Gender (% male)	42·8	–	39·2	–	45·4*	–
Race (% African American)	51·2	–	60·9*	–	44·2	–
Poverty status (%)	–	–	42·0	–	58·0	–
BMI (kg/m^2)	30·26	8·03	29·86	8·55	30·55	7·63
Diagnosed diabetes (%)	16·5	–	16·7	–	16·3	–
SBP (mmHg)	120·80	17·79	121·15	18·77	120·56	17·04
Current illicit drug use (%)	5·9	–	8·9*	–	3·7	–
Current alcohol use (%)	52·5	–	49·7	–	54·5*	–
Current cigarette use (%)	49·1	–	57·6*	–	42·9	–
HEI-2010 total score	42·62	11·46	42·09	11·27	43·01	11·59
CES-D total score	15·68	11·74	17·99***	12·12	14·00	11·17
CVLT-II list A recall	21·60	9·90	21·60	8·93	21·60	10·55
CVLT-II short-delay free recall	7·14	3·08	6·76	2·94	7·44***	3·15
CVLT-II long-delay free recall	7·22	3·10	6·87	2·92	7·48***	3·21
CVLT-II learning slope	1·69	1·07	1·67	1·04	1·71	1·09
BVRT errors	6·81	5·18	7·19**	5·47	6·54	4·95
Digit Span Forward	6·98	2·48	6·73	2·37	7·17***	2·55
Digit Span Backward	5·40	2·38	5·04	2·18	5·67***	2·48
TMT A	38·87	47·32	41·83*	52·98	36·72	42·65
TMT B	156·39	165·43	183·02***	181·27	137·09	150·08
Card Rotations Test	34·85	17·87	31·93	17·59	37·20***	17·75
Identical Pictures Test	23·12	6·50	22·06	6·10	23·99***	6·68
Semantic Fluency Test	18·52	5·21	17·78	4·83	19·05**	5·40

SBP, systolic blood pressure; HEI-2010, Healthy Eating Index-2010; CES-D, Center for Epidemiologic Studies Depression Scale; CVLT-II, California Verbal Learning Test-II; BVRT errors, Benton Visual Retention Test total errors; TMT, Trail Making Test.
Mean value or percentage is significantly higher: *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

Table 2 Unadjusted associations between Healthy Eating Index-2010 (HEI-2010) scores and cognitive test scores among White and African American men and women (n 2090; 57 % female, mean age 47·9 years) from urban neighbourhoods in Baltimore, MD, USA; Healthy Aging in Neighborhoods of Diversity across the Life Span (HANDLS) study

	CVLT-II list A	CVLT-II short	CVLT-II long	CVLT-II slope	BVRT errors	Digit Span Forward	Digit Span Backward	TMT A	TMT B	Card Rotations Test	Identical Pictures Test
HEI-2010	0·05*	0·01	0·03	0·05*	−0·004	−0·01	−0·01	−0·02	−0·02	0·05	0·01

CVLT-II, California Verbal Learning Test-II; CVLT-II list A, CVLT-II list A total recall; CVLT-II short, CVLT-II short-delay free recall; CVLT-II, long, CVLT-II long-delay free recall; CVLT-II slope, CVLT-II learning slope; BVRT errors, Benton Visual Retention Test total errors; TMT, Trail Making Test.
Significant association: *$P < 0.05$.

Table 3 Associations of Healthy Eating Index-2010 (HEI-2010) scores and race and poverty interaction terms with cognitive outcomes in sequential linear regression models among White and African American men and women (n 2090; 57 % female, mean age 47·9 years) from urban neighbourhoods in Baltimore, MD, USA; Healthy Aging in Neighborhoods of Diversity across the Life Span (HANDLS) study

| | Block 1: adjusted for covariates† | Block 2: HEI-2010 score | | | Block 3: race and poverty interactions | | | | |
| | | | | | HEI × race | | HEI × poverty status | | |
	R^2	B	SE	ΔR^2	B	SE	B	SE	ΔR^2
Verbal memory									
CVLT-II list A recall	0·06	0·05**	0·02	0·004	0·03	0·04	0·03	0·04	0·001
CVLT-II short-delay free recall	0·19	0·004	0·01	<0·001	0·02	0·01	0·004	0·01	0·001
CVLT-II long-delay free recall	0·20	0·01	0·01	0·001	0·01	0·01	0·01	0·01	<0·001
CVLT-II learning slope	0·03	0·01*	0·002	0·003	0·003	0·004	0·001	0·01	<0·001
Non-verbal memory									
BVRT total errors	0·15	−0·01	0·01	<0·001	0·02	0·02	−0·03	0·02	0·001
Working memory									
Digit Span Forward	0·06	−0·003	0·01	<0·001	−0·01	0·01	0·01	0·01	0·001
Digit Span Backward	0·09	−0·002	0·004	<0·001	−00·01	0·01	0·01	0·01	0·001
Attention and cognitive flexibility									
TMT A	0·18	−0·16	0·09	<0·001	−0·01	0·19	0·10	0·19	<0·001
TMT B	0·13	−0·53	0·31	<0·001	0·46	0·62	−1·37*	0·64	0·002
Visuospatial ability									
Card Rotations Test	0·18	0·06	0·04	<0·001	−0·07	0·08	0·21**	0·08	0·004
Perceptual speed									
Identical Pictures Test	0·32	0·01	0·01	<0·001	−0·03	0·02	0·05*	0·02	0·002
Semantic fluency									
Semantic Fluency Test	0·11	−0·001	0·01	<0·001	−0·01	0·02	−0·01	0·02	<0·001

CVLT-II, California Verbal Learning Test-II; BVRT errors, Benton Visual Retention Test total errors; TMT, Trail Making Test.
Significant association: *$P < 0.05$, **$P < 0.01$.
†Covariates included in these models were age, race, sex, education, poverty status, Center for Epidemiologic Studies Depression Scale score, current alcohol use (yes/no), current cigarette smoker (yes/no), BMI, mean systolic blood pressure and diabetes status.

($B = 0.05$, $P < 0.01$) and CVLT-II learning slope ($B = 0.01$, $P < 0.05$), suggesting that higher diet quality was associated with better verbal learning and memory.

Non-verbal memory
After adjustment for covariates, there were no significant relationships of HEI-2010 scores with performance on the Benton Visual Retention Test. No significant interactions emerged.

Working memory
After adjustment for covariates, there was no significant association between HEI-2010 scores and Digit Span Forward and Backward performance. No significant interactions emerged.

Attention and cognitive flexibility
There were no significant main effects of HEI-2010 scores on TMT A or TMT B performance (block 2); however, there was a significant HEI-2010 by poverty status interaction in block 3 ($B = -1.37$, $P < 0.05$). A plot of the interaction showed that the negative linear association between HEI-2010 scores and time to complete the TMT B task was steeper when participants were below the poverty threshold (see Fig. 1(a)).

Visuospatial ability
There were no significant main effects of HEI-2010 scores on Card Rotations Test performance (block 1); however, there was a significant HEI-2010 by poverty status interaction in block 3 ($B = 0.21$, $P < 0.01$). A plot of the
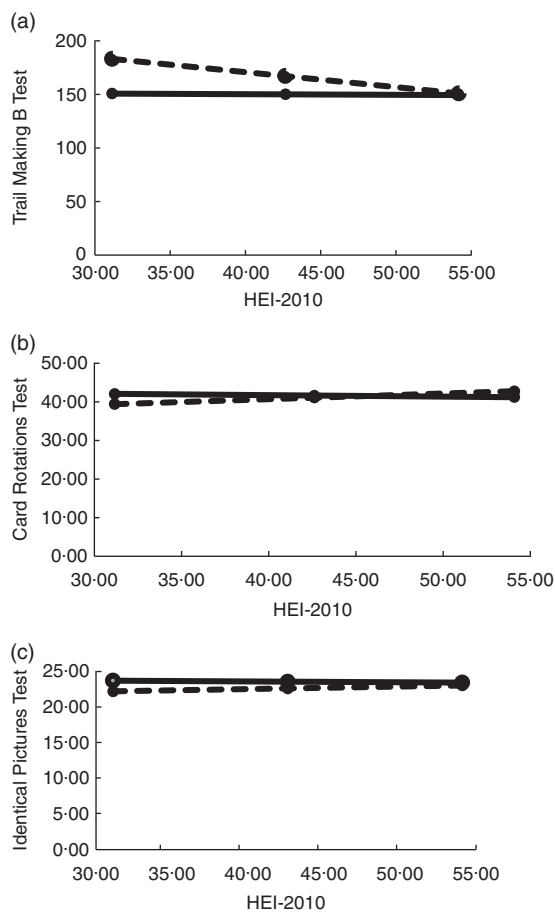
Fig. 1 Interaction between Healthy Eating Index-2010 (HEI-2010) score and poverty status (—●—, above the poverty line; – ● -, below the poverty line) among White and African American men and women (*n* 2090; 57 % female, mean age 47·9 years) from urban neighbourhoods in Baltimore, MD, USA; Healthy Aging in Neighborhoods of Diversity across the Life Span (HANDLS) study. HEI-2010 score by poverty status interaction predicting performance on: (a) the Trail Making Test B (illustrating the relationship of HEI-2010 scores with time to complete the test in both poverty groups); (b) the Card Rotations Test (illustrating the relationship of HEI-2010 scores with number correct on the test in both poverty groups); and (c) the Identical Pictures Test (illustrating the relationship of HEI-2010 scores with number correct on the test in both poverty groups)

interaction showed that the positive linear association between HEI-2010 scores and Card Rotations Test scores was more pronounced among participants below the poverty threshold. There was no association among participants above the poverty threshold (see Fig. 1(b)). Thus, higher diet quality resulted in better visuospatial performance for those with less income, but did not have an effect for those with higher income.

Perceptual speed

There were no significant relationships of HEI-2010 scores with Identical Pictures Test performance. However, there was a significant HEI-2010 by poverty status interaction ($B = 0·05$, $P < 0·05$). A plot of the interaction showed a steep positive linear association between HEI-2010 scores and Identical Pictures Test total correct among participants below the poverty threshold, while the slope for those above the poverty threshold was relatively flat (see Fig. 1(c)). Similar to the aforementioned findings, better diet quality was related to better perceptual speed performance among those with less income.

Semantic fluency

After adjustment for covariates, there were no significant relationships of HEI-2010 scores with performance on the Semantic Fluency Test. No significant interactions emerged.

Discussion

The present investigation is, to our knowledge, the first to examine potential interactive relationships of diet quality (as defined by HEI-2010 scores), race and poverty status with multiple measures of cognitive function. Results revealed significant interactive relationships of diet quality and poverty status with performance on several measures of cognitive function among a diverse sample of urban adults. Specifically, when diet quality was higher, performance in the domains of attention and cognitive flexibility, visuospatial ability and perceptual speed was better among those with lower SES. In addition, higher diet quality was associated with better performance on two measures of verbal learning and memory, irrespective of race and poverty status.

The current findings suggest that better diet quality may play a protective role for cognitive function (across multiple domains) among the poorest. These findings are quite surprising given that the overall quality of the diet for the total sample and both poverty status groups was quite low. Cognitive function in our sample was lower, in general, among those in the low poverty status group. This finding is consistent with substantial evidence that shows cognitive function is lower among adults with lower SES[42]. It is plausible that even a minimally healthful dietary pattern is beneficial in the sample. Participants who make more healthful food choices despite their limited economic means may be making choices that are ultimately helping to preserve their cognitive health.

Preliminary evidence suggests that poor-quality diets reflecting at least some adherence to dietary guidelines may show some benefits for health among the poor. For example in a previous HANDLS study analysis of chronic kidney disease, among individuals living in poverty, those who were somehow able to follow a healthful diet derived more of a renal health benefit than those with fewer economic disadvantages[43]. In that case, closer adherence to the DASH (Dietary Approaches to Stop Hypertension) diet carried greater benefit for low-SES individuals than for those with higher SES. Potential public health implications may therefore include a greater emphasis on improving

the diets of socio-economically disadvantaged populations to improve or preserve cognitive function.

The finding that higher diet quality was associated with better verbal learning and memory performance in all participants is consistent with similar findings for other well-known measures of diet quality and dietary pattern. Among older adults enrolled in a Mediterranean diet intervention supplemented with extra-virgin olive oil, adherence to the intervention was associated with significantly better verbal learning and memory performance and less mild cognitive impairment over time after adjustment for age, sex, smoking, alcohol, diabetes, dyslipidaemia, hypertension, apo E genotype, physical activity, education, family history of cognitive impairment/dementia, BMI and total energy intake[12]. A study that examined the long-term impact of overall dietary patterns on cognition showed that a dietary pattern defined as healthful was associated with better verbal learning and memory performance over 13 years as compared with less healthful patterns[44]. Within the HANDLS study, a prior analysis of the association between antioxidants and cognitive function yielded cross-sectional evidence that greater vitamin E intake was associated with better verbal learning and memory performance[14].

There is at least one plausible explanation for the link between diet quality and verbal learning and memory, specifically. Verbal learning and memory performance is particularly sensitive to cardiovascular and metabolic health indices that are linked to poor diet quality[45,46]. Inasmuch as individuals with poor diet quality are at risk for developing conditions that negatively influence verbal memory, they may also show preclinical decrements in verbal learning and memory that are detectable by sensitive cognitive measures.

Our significant findings were particularly striking given that the HEI-2010 may not be an optimal assessment of dietary intake. The DGA has provided federal nutritional guidance for Americans for nearly four decades; however, there is some evidence that these guidelines may not adequately apply to the socio-economic, cultural and ethnically diverse population of the USA[47]. For example, some evidence suggests that African American adults have gained more weight, and adults with low income have experienced higher rates of chronic disease, when following DGA guidelines[48]. Another major criticism of the DGA and similar guidelines is that they do not take into account 'real world' factors that affect compliance to guidelines and that input is not derived from diverse groups or stakeholders when creating the guidelines[7]. It follows, therefore, that an assessment designed to measure compliance to these federal guidelines may underestimate the quality of the diet in a heterogeneous population such as in the HANDLS study. These limitations may help to partially explain the low HEI-2010 scores for the sample. Importantly, despite having utilized a less than ideal measure of diet quality, we documented several significant

associations, suggesting that the benefit of a healthy diet on cognitive function is likely underestimated in the present investigation.

Several studies have suggested that diet quality tends to vary as a function of race[15], with African Americans having poorer dietary patterns[16]; however, in our study, there were no significant differences in HEI-2010 scores by race and no race interactions emerged. This finding was surprising given the aforementioned literature. Both racial groups had HEI-2010 scores just above 40, indicating poor overall diet quality for both of the predominant racial groups in urban Baltimore, despite possible cultural differences in eating patterns[49]. It is possible that a lack of sensitivity of the HEI-2010 may have played a role in non-significant mean differences in HEI-2010 scores between race and poverty status groups. While the total score relies on whole food groups, other indices of diet quality that consider macronutrients and micronutrients may be more sensitive to subtle differences in the nutritional content of the diet between races. Future studies should consider more sensitive measures of diet quality such as the mean adequacy ratio to test this hypothesis. Non-significant mean differences in HEI-2010 total score between poverty status groups are also contrary to the literature supporting an association between diet quality and SES. There were more participants that fell into the higher income group than the low income group which may have played a role. Future research may consider factors that promote low diet quality among higher-SES groups.

In general, effect sizes for significant associations were small; therefore, interpretation of findings should be approached with caution. Yet, the pattern of associations suggests that diet quality and cognitive function are likely related at the population level, although it is not yet clear whether the association is clinically significant for individuals. It is premature, therefore, to suggest that interventions aimed at improving overall diet quality would improve cognitive function in this population. Furthermore, it is important to view our findings in the context of the sample's poor overall diet quality for both African Americans and Whites, as well as for those above and below the poverty threshold. Individuals in the study showed poor adherence to the DGA. A prior analysis showed that HANDLS participants had low adherence to other healthful dietary patterns such as the Mediterranean diet and DASH eating pattern, but adhered mainly to a Western dietary pattern[50]. Therefore, our findings are unlikely to generalize to individuals with more healthful dietary patterns. Future studies are needed to test these associations in a larger, more heterogeneous sample with respect to diet quality, SES and race.

Our study has several strengths. First, the HANDLS study consists of a large representative sample of urban-dwelling adults. Importantly, the sample had a large proportion of African Americans, a population that is often under-recruited and understudied. Few studies of

cognitive function provide such rich data on African Americans. Second, diet quality was based on two 24 h recalls. Most studies that assess diet quality include only one recall. Lastly, the diet quality and cognitive function relationship has been examined in prior studies using the HEI-2005, and those studies showed a null and positive association between diet quality and cognitive function, respectively[51,52]. However, we are unaware of similar studies that have employed the HEI-2010 score, an index that has undergone significant improvements from its previous iteration. As such, our study makes a unique contribution to both the nutrition and cognition literature.

Our study has some limitations. The directionality of the relationships that emerged in the study can only be inferred due to the cross-sectional nature of the analysis. It is possible that reduced cognitive performance may precede poor diet quality. Future analyses will examine the prospective association between changes in diet quality and cognitive performance. Another limitation of the current study is its reliance on memory-based dietary recall. Human memory is an acceptable but inexact method for assessing past food consumption behaviour. Finally, although the findings cannot be generalized to a national population, independent demographic analyses found this sample is representative of urban populations from US cities with similar population densities and racial distributions (J Lepkowski, unpublished results).

Conclusion

Overall, our findings lend insight into understanding the potential influence of overall diet quality on cognitive function in an urban-dwelling population and how the association varies by SES group membership. Poor diet quality in our sample suggests a need for heightened awareness of optimal dietary patterns, including more healthful dietary patterns that can be achieved across varying socio-economic groups with potentially limited food access. Diet quality measures that are more comprehensive and more sensitive to cultural dietary patterns may help to further illuminate links between diet and cognitive function.

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