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Dietary lutein and zeaxanthin are associated with working memory in an older population

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Abstract

Objective: The purpose of the study was to examine the association between dietary lutein and zeaxanthin (L + Z) intake and immediate word recall (IWR) and delayed word recall (DWR), and to identify the major contributors to dietary L + Z intake in a recent and representative sample of the older US population.
Design: In this cross-sectional analysis, multivariate path analytic models estimated the association between L + Z consumption and cognitive performance while adjusting for covariates.
Setting: Observations were drawn from the 2014 Health and Retirement Study, a nationally representative panel study of older US adults, and the 2013 Health Care and Nutrition Study, which assessed dietary intake via FFQ in a subsample of respondents.
Participants: The analytic sample included 6390 respondents aged ≥50 years.
Results: L + Z intake was 2·44 ± 2·32 mg/d on average, and L + Z intake differed significantly across quartiles ($P < 0·001$). For example, average L + Z intake in Q1 was 0·74 ± 0·23 mg/d and in Q4 was 5·46 ± 2·88 mg/d. In covariate adjusted models, older adults in the highest quartiles of L + Z intake had significantly greater IWR and DWR scores than those in the lowest quartile. Leafy vegetables, cruciferous vegetables, dark yellow vegetables, fish and seafood, legumes, eggs and fruit were significant and meaningful predictors of dietary L + Z intake.
Conclusion: A high consumption of vegetables, fish and seafood, legumes, eggs and fruit is associated with a higher intake of L + Z and greater word recall among older adults.

Keywords
Cognition
Older adult
Lutein
Carotenoid
Memory
Zeaxanthin
Episodic memory

Lutein and zeaxanthin (L + Z) belong to the xanthophyll family of carotenoids, commonly found in yellow, orange and dark green fruits and vegetables, including kale, spinach and carrots. L + Z are commonly associated with eye health, as they are the main dietary carotenoids found in the retina of humans, and protect the macula from blue light damage and enhance visual acuity[1]. Additionally, L + Z have been found to be the predominant carotenoids in the brain of both infants and older adults, making up approximately two-thirds of the overall carotenoid concentrations found in the brain[2–4]. Emerging evidence suggests that L + Z may play a critical role in the development and preservation of cognitive function across the lifespan[5,6].

Higher serum L + Z levels have been correlated with a lower likelihood of developing dementia and Alzheimer's disease, as well as a reduced risk of Alzheimer's disease-related mortality in older adults[7,8]. A recent cross-sectional analysis of older US adults identified higher dietary intakes of L + Z to be associated with greater cognitive performance across multiple cognitive domains[9]. Macular pigment optical density, a biomarker of L + Z status, was positively associated with cognitive performance in both healthy, community-dwelling older adults[10] and individuals with mild cognitive impairment[11]. The few randomised controlled trials exploring L + Z supplementation in older adults have demonstrated cognitive benefits of these carotenoids[12–14]. Four months of L + Z supplementation (12 mg/d), with or without DHA, resulted in a significant improvement in verbal fluency scores of older women[12]. More recently, 12 months of supplementation in community-dwelling older adults significantly

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improved complex attention and cognitive flexibility[14], and those with higher serum and retinal L + Z levels demonstrated enhanced neural efficiency[15]. Previous L + Z supplementation trials have utilised approximately 10–12 mg/d of L + Z to elicit cognitive benefits, yet the average US adult consumes approximately 1–2 mg/d of L + Z[16]. Therefore, it is important to identify the dietary L + Z intakes that elicit cognitive benefits and the most significant dietary sources of L + Z in older US adults.

Most of the available observational research on cognitive benefits of L + Z has been limited to identifying the relationship between L + Z intake and risk of neurodegenerative diseases rather than current cognitive performance. Evaluating the maintenance of cognitive health is important in understanding L + Z's role in the delay of cognitive impairment. In addition, only two of the few population-based studies available were conducted in a sample from the US population[8,9]. The purpose of the current study was to examine the association between dietary L + Z intake and cognitive function in a recent and nationally representative sample of the older US population. Additionally, we aimed to identify the major contributors to dietary L + Z intake in older adults.

Experimental methods

Observations were drawn from the Health and Retirement Study (HRS), a nationally representative panel study of older US adults beginning in 1992 with biennial follow-up. The HRS uses a dual-modality interview approach with around 43 % of interviews in 2014 administered face-to-face and 57 % of interviews administered through telephone. The 2013 Health Care and Nutrition Study (HCNS) is a supplemental off-year mail-out study measuring food consumption in a subsample of HRS respondents and is based on the Harvard FFQ developed by Willett and colleagues[17] and utilises nutrient tables developed by the Harvard School of Public Health[18]. The HRS is funded by the National Institute on Aging (NIA) and the Survey Research Center at the University of Michigan, and the HCNS was funded by the NIA (U01 AG009740) and conducted by the Survey Research Center of the Institute for Social Research at the University of Michigan[19]. The study was deemed to be eligible for exemption by the Texas State University IRB.

In late 2013, questionnaires were mailed to a subsample of HRS respondents (n 12 418) with 8073 respondents completing the HCNS (simple response rate = 65 %). The final data contained 8035 respondents, with 97 % of them answering ≥90 % of the food consumption questions. Of the 8035 HCNS respondents with complete food consumption data, 238 were removed from the analytic sample due to reported age being <50 years, 581 were removed due to daily energy intakes falling outside the commonly used allowable range of 2092–14644 kJ/d for women and 3347–16736 kJ/d for men[20], 643 were removed with missing word recall scores in 2014, as were 162 respondents reporting a previously diagnosed memory-related disease. Finally, twenty-one cases with invalid population weights were removed, resulting in an analytic sample size of 6390.

L + Z intake and food groups: The HCNS FFQ asked respondents to report average number of servings of 164 unique food items over the past 12 months, which were converted to daily portion sizes. Missing data was imputed based on six food items with the least missing data as well as respondents' race/ethnicity, gender, years of education and BMI. A list of other food items eaten at least once per week was mapped to the nutrient dataset, then totals for each nutrient were calculated[19]. The measure of L + Z examined was a sum of both L + Z intake reported in milligrams. For models estimating the association between L + Z and word recall, quartiles of L + Z were calculated, and the lowest quartile was used as the reference category.

For the analyses identifying the foods that contributed the most to L + Z intake, food items were grouped, and five food items were excluded from analysis based on recommendations provided by the Food Patterns Equivalence Database by the United States Department of Agriculture[21]. The remaining 159 food items were grouped based on nutritional similarity, then summed to represent daily intake of thirty-five separate food groups. Table 4 describes the food groups and excluded food items. For clarity, we use the term 'food groups' to describe the thirty-five separate foods and food groups used to identify dietary profiles. Due to non-normality in certain food groups, scores were log-transformed with an offset of 0·01 to improve normality and allow inclusion of individuals reporting non-intake of a given food group.

Cognitive function: The association between L + Z intake and cognitive function was evaluated on the cognitive domain of working memory. Episodic memory is particularly useful in measuring subclinical changes in cognitive performance among aging adults[22]. Working memory and fluid processing ability measures were assessed using immediate word recall (IWR) and delayed word recall (DWR) scores. These two tests (IWR and DWR) measure episodic verbal memory via free recall and have been demonstrated to be sensitive to changes in fluid cognitive abilities[23]. The IWR score was measured by giving ten words from a list of common nouns and asking the respondent to recall them immediately after hearing the list, with the number of words correctly recalled providing the IWR score[24]. After an estimated 5 min of additional questioning had passed, the interviewer asked the participant to recall the words again, and the number of words correctly recalled was the DWR score.

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Covariates: Measures taken from the 2014 HRS were included as covariates to adjust for risk factors of cognitive decline and to reduce the likelihood of alternative explanations when interpreting our results. Indicators of respondents' demographic characteristics included age, gender (1 = female, 0 = male), race/ethnicity (White, Black, Hispanic, other), marital status (1 = partnered or married, 0 = single, divorced or widowed) and retirement status (1 = retired, 0 = not retired). Measures of socioeconomic context included education (<12 years of education, 12 years of education, >12 years of education), longest occupational tenure (white-collar, blue-collar, female homemaker, other occupational tenure) and log-transformed household income and assets. Measures of obesity and health behaviours included BMI (underweight: BMI < 18·5 kg/m^2; normal weight: 18·5 kg/m^2 ≤ BMI < 25 kg/m^2; overweight: 25 kg/m^2 ≤ BMI < 30 kg/m^2; obese: BMI ≥ 30 kg/m^2), vigorous physical activity (participation in activities such as sports, heavy housework or a job that involves physical labour, classifiable into no vigorous physical activity, vigorous physical activity less than once per week and vigorous physical activity more than

Table 1 Descriptive statistics for participant characteristics for analytic sample by lutein and zeaxanthin quartiles, Health Care and Nutrition Study 2013/Health and Retirement Study 2014

				Lutein and zeaxanthin quartiles							
	Overall			Q1		Q2		Q3		Q4	
Continuous covariates	*n*	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Age	6390	65·32	10·14	65·43	10·14	65·70	10·08	65·41	10·13	64·70	10·16
Household income*	6390	8·69	11·78	6·60	7·87	7·31	8·12	10·18	12·06	10·96	16·64
Household assets*	6390	53·75	110·96	35·03	71·65	39·11	68·69	67·09	135·89	76·62	142·69
Chronic conditions	5989	2·08	1·47	2·22	1·48	2·24	1·47	2·00	1·46	1·85	1·42
Mobility limitations	5918	2·54	3·02	3·25	3·24	2·74	3·01	2·19	2·95	1·88	2·74
Categorical covariates	*n*	%		%		%		%		%	
Gender											
Male	2559	44·48		48·00		46·95		46·47		35·71	
Female	3831	55·52		52·00		53·05		53·53		64·29	
Race/ethnicity											
White	4482	79·76		83·38		79·73		79·78		75·71	
Black	993	9·10		6·28		9·09		10·14		11·18	
Hispanic	718	7·93		7·04		8·79		6·35		9·68	
Other	192	3·15		3·30		2·27		3·67		3·40	
Marital status											
Single	2301	34·80		37·93		35·61		32·11		33·27	
Married/partnered	4088	65·20		62·07		64·39		67·89		66·73	
Retirement status											
Not retired	2953	51·76		48·30		47·09		54·87		57·47	
Retired	3406	48·24		51·70		52·91		45·13		42·53	
Education											
<High school degree	1058	13·56		18·23		13·14		11·87		10·59	
High school degree	2091	31·69		39·88		34·13		28·01		23·75	
>High school degree	3241	54·75		41·89		52·73		60·11		65·66	
Occupational tenure											
White-collar	2663	41·06		36·28		40·89		42·23		45·34	
Blue-collar	1485	22·40		28·24		24·56		19·51		16·58	
Homemaker	130	1·69		2·28		1·66		1·18		1·63	
Other	2113	34·87		33·27		32·90		37·09		36·46	
BMI											
Underweight	81	1·23		1·48		1·11		0·80		1·56	
Normal	1680	26·99		25·15		25·63		25·83		31·75	
Overweight	2332	36·75		36·54		37·31		37·94		35·12	
Obese	2220	35·02		36·83		35·96		35·42		31·57	
Vigorous activity											
None	3379	50·72		62·58		54·00		44·16		40·81	
Some	1367	22·38		20·31		23·29		23·05		22·97	
Regular	1628	26·90		17·11		22·71		32·79		36·22	
Smoking status											
Non-smoker	5675	88·20		81·25		88·29		90·60		93·35	
Current smoker	681	11·80		18·75		11·71		9·40		6·65	
Alcohol consumption											
None	3831	57·09		63·70		60·17		53·98		49·61	
Moderate	2116	35·57		30·03		33·16		38·60		41·21	
Heavy	385	7·34		6·27		6·67		7·42		9·18	

Means and percentages adjusted for complex survey design and may not match percentages based on non-weighted sample sizes.
*Household income and household assets reported on $10 000s; statistical tests based on log-transformed household income and assets.

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Table 2 Descriptive statistics for lutein and zeaxanthin consumption and cognitive measures, Health Care and Nutrition Study 2013/Health and Retirement Study 2014

			Overall		Lutein and zeaxanthin quartiles									
					Q1		Q2		Q3		Q4			
Measure	Year	*n*	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*F*	*P*
Lutein and zeaxanthin (mg/d)	2013	6390	2·44	2·32	0·74	0·23	1·48	0·22	2·38	0·31	5·46	2·88	3268·52	<0·001
Immediate word recall	2014	6390	5·62	1·66	5·34[a]	1·61	5·52[a,b]	1·63	5·71[b]	1·68	5·97	1·67	40·28	<0·001
Delayed word recall	2014	6390	4·63	1·99	4·33[a]	1·91	4·53[a,b]	1·96	4·71[b]	2·01	4·99	2·02	31·39	<0·001

Means adjusted for complex survey design.
[a,b]Matching superscript letters denote non-significant pairwise comparison.

once per week), current smoking status (1 = current smoker, 0 = no current smoker) and alcohol consumption (non-drinkers; moderate drinkers – men: 1–14 drinks per week, females: 1–7 drinks per week; and heavy drinkers – men: >14 drinks per week, females: >7 drinks per week). Health status was measured as a sum of doctor-diagnosed chronic conditions (high blood pressure, cancer, diabetes, lung disease, heart problems, stroke, psychiatric problems and arthritis), and disability was measured as the sum of eleven indicators of limitation in physical mobility (difficulty in any of the following activities: stooping or crouching, climbing one flight of stairs without resting, climbing several flights of stairs without resting, moving large objects, sitting in a chair for 2 hours, getting up from a chair after sitting for a long period, lifting weights >10 pounds, raising arms above shoulder level, walking one block, walking several blocks, picking up a dime from a table). Mobility limitations were log-transformed with an offset of 0·1 to adjust for non-normality (excluding descriptive statistics).

Statistics

Multivariate path analytic models with traditional multiple regression assumptions for normally distributed outcomes were used to test whether estimated L + Z intake in 2013 was associated with immediate and delayed word recall status in 2014. The models were jointly estimated, meaning that IWR and DWR were regressed on L + Z quartiles and covariates in a single statistical model, allowing an adjustment for the correlation between IWR and DWR outcome measures. To identify which food groups were most strongly associated with estimated L + Z intake, L + Z intake was regressed on the thirty-five food groups in a multiple regression model. Standardised regression estimates were produced to identify which food groups were most strongly associated with L + Z levels. Mplus (version 8.1) was used to estimate both the multivariate path analytic models and the L + Z food group regression while adjusting for the complex sampling design of HRS and multicollinearity between independent variables, as well as addressing missing data through maximum likelihood[25]. Bivariate associations among L + Z intake, word recall and participant characteristics were estimated using SAS (version 9.4)[26]. For L + Z intake and cognitive outcome measures, overall differences across L + Z intake quartiles were estimated using ANOVA with bivariate follow-up through least squares mean differences. To reduce the likelihood of type 1 error due to multiple comparisons, the significance level for each follow-up test was adjusted using Bonferroni correction. All statistical estimates were adjusted for complex survey design.

Results

Table 1 displays the demographic characteristics of study participants across quartiles of L + Z intake. The average age of participants at baseline was 65·3 years, and the majority of the sample was female (55·5 %) and White (79·8 %).

As shown in Table 2, mean L + Z intake in the sample was 2·4 mg/d. Mean IWR and DWR significantly differed

Table 3 Regression estimates from models regressing immediate and delayed word recall on lutein and zeaxanthin intake quartiles, 2013 Health Care and Nutrition Study/2014 Health and Retirement Study

	Est	SE	*P*
Immediate word recall			
Lutein and zeaxanthin intake			
Quartile 1 (reference)			
Quartile 2	0·07	0·06	0·267
Quartile 3	0·13	0·07	0·051
Quartile 4	0·25	0·07	<0·001
Delayed word recall			
Lutein and zeaxanthin intake			
Quartile 1 (reference)			
Quartile 2	0·09	0·08	0·242
Quartile 3	0·14	0·08	0·076
Quartile 4	0·28	0·08	0·001

n 6390; all models adjusted for the following covariates: age, log-transformed household income, log-transformed household assets, doctor-diagnosed chronic conditions, log-transformed mobility limitations, gender, race/ethnicity, marital status, retirement status, education, longest occupational tenure, BMI, vigorous physical activity, smoking status and alcohol consumption.

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by L + Z quartile. Those in the highest quartile of L + Z intake had significantly greater immediate and delayed word recall scores than all other quartiles, and those in Q3 had significantly greater IWR and DWR compared to those in Q1. Generally, those above the median of L + Z intake appeared to have better working memory at baseline than those in the lowest L + Z intake quartile.

Table 3 includes regression estimates from the multivariate path analytic models regressing immediate and delayed word recall scores on L + Z quartiles while adjusting for covariates. When examining differences by L + Z quartile, L + Z intake appeared to be positively associated with baseline IWR and DWR. For example, respondents in Q4 had IWR scores that were 0·25 unit greater (SE = 0·07, $P < 0·001$) and DWR scores that were 0·28 unit greater (SE = 0·08, $P = 0·001$) than respondents in the lowest quartile of L + Z intake.

Table 4 lists the food items that were categorised in the thirty-five food groups used to predict L + Z intake as shown in Table 5. Table 5 is sorted by the direction and magnitude of standardised regression estimates, indicating which food groups were the strongest contributors to L + Z intake. Leafy vegetables, cruciferous vegetables, dark yellow vegetables, fish and seafood, legumes, eggs, fruit, whole grain and fruit juice were significantly positively associated with L + Z intake, and red meat and mayonnaise and creamy dressing were negatively associated with L + Z intake, at the significance level of $P < 0·001$. The *r*-squared for the regression was 0·737, indicating that 73·7 % of the variation in L + Z intake was attributable to the food groups included in the model.

Discussion

In a nationally representative sample of older US adults, individuals with higher L + Z intakes had better episodic memory performance. Episodic memory – the ability to recall and elicit an event from a specific time and place – declines with age, especially after 60 years of age[27–29]. Lower episodic memory scores have previously been demonstrated to be a significant predictor of mild

Table 4 Food groupings used to estimate lutein + zeaxanthin intake, 2013 Health Care and Nutrition Study

Food groups	Food items
Leafy vegetables	Spinach cooked, spinach raw, head lettuce, leaf lettuce
Cruciferous vegetables	Broccoli, cabbage, cauliflower, brussels sprouts, kale/mustard/chard greens
Dark yellow vegetables	Carrots raw, carrots cooked, winter squash, yams/sweet potatoes
Fish and seafood	Tuna canned, fish sticks, seafood main dish, fish dark, fish other
Legumes	Beans or lentils, tofu soy protein, peas or lima beans
Eggs	Eggs regular, egg whites, eggs fortified
Fruit	Raisins or grapes, prunes/dried plums, applesauce, apples/pears, apricots
Whole grain	Whole-grain bread, rice brown, oatmeal, rye bread, cooked cereal other
Fruit juice	Prune juice, apple juice, orange juice fortified, orange juice regular, grapefruit juice
Other vegetables	Onions raw, onions cooked, corn, mixed vegetables, summer squash
Tea	Tea with caffeine, decaffeinated tea
Nuts	Peanut butter, peanuts, walnuts, nuts other
Olive oil	Olive oil
Organ meat	Liver beef/pork, liver chicken/turkey
Condiments	Non-dairy cream, jams/preserves/honey, ketchup/red chilli sauce, salt added, number of teaspoons of sugar
High-fat dairy	Whole milk, cream, regular ice cream, cottage/ricotta cheese, cream cheese
Sweets	Milk chocolate, dark chocolate, candy bars, candy without chocolate, reduced fat cookies
Alcohol	Beer regular, beer light, red wine, white wine, liquor
Processed meats	Bacon, beef/pork hot dogs, chicken/turkey hot dogs, processed meat, processed meat other
High-energy drinks	Carbonated with caffeine and sugar, carbonated with sugar other, sugar beverage other
French fries	French fries
Refined grains	White bread, bagels, muffins/biscuits, rice white, pasta
Coffee	Coffee with caffeine, decaffeinated coffee, dairy coffee drink
Cream soup	Cream soup
Low-fat dairy	Skim milk, 1 or 2 % milk, soy milk, frozen yogurt/low-fat ice cream, flavoured yogurt
Snacks	Potato chips, crackers, crackers whole grain, crackers other, popcorn light
Pizza	Pizza
Tomatoes	Tomatoes, tomato or v8 juice, tomato sauce, salsa
Butter and margarine	Butter, spreadable butter, margarine
Poultry	Chicken/turkey, chicken/turkey with skin, chicken/turkey without skin
Cold cereal	Cold cereal
Low-energy drink	Low-calorie carbonated with caffeine, low-calorie carbonated without caffeine
Potatoes	Potatoes
Red meat	Lean hamburger, regular hamburger, beef/pork/lamb – mix, pork main dish, beef/lamb main
Mayonnaise and creamy dressing	Mayonnaise regular, salad dressing

Food items excluded from analysis: Splenda, artificial sweetener, garlic, low-carbohydrate bars, plain water.
Some individual food items were not collapsed into groups due to the combination of multiple food items used to produce the food (i.e. pizza) or having varying preparation techniques (i.e. potatoes).

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Table 5 Standardised regression estimates identifying food groups as primary contributors to lutein and zeaxanthin intake, 2013 Health Care and Nutrition Study

	B	SE	*P*
Leafy vegetables	0·50	0·02	<0·001
Cruciferous vegetables	0·32	0·02	<0·001
Dark yellow vegetables	0·07	0·02	<0·001
Fish and seafood	0·07	0·01	<0·001
Legumes	0·06	0·02	<0·001
Eggs	0·06	0·01	<0·001
Fruit	0·06	0·01	<0·001
Whole grain	0·05	0·01	<0·001
Fruit juice	0·04	0·01	<0·001
Other vegetables	0·04	0·02	0·021
Tea	0·03	0·01	0·005
Nuts	0·02	0·01	0·019
Olive oil	0·02	0·01	0·031
Organ meat	0·02	0·01	0·075
Condiments	0·01	0·01	0·107
High-fat dairy	0·01	0·01	0·230
Sweets	0·01	0·01	0·445
Alcohol	0·00	0·01	0·742
Processed meats	0·00	0·01	0·776
High-energy drinks	0·00	0·01	0·732
French fries	0·00	0·01	0·981
Refined grains	0·00	0·01	0·815
Coffee	0·00	0·01	0·807
Cream soup	−0·01	0·01	0·380
Low-fat dairy	−0·01	0·01	0·196
Snacks	−0·01	0·01	0·145
Pizza	−0·01	0·01	0·086
Tomatoes	−0·02	0·01	0·187
Butter and margarine	−0·02	0·01	0·015
Poultry	−0·02	0·01	0·051
Cold cereal	−0·02	0·01	0·005
Low-energy drink	−0·02	0·01	0·002
Potatoes	−0·03	0·01	0·003
Red meat	−0·03	0·01	<0·001
Mayonnaise and creamy dressing	−0·05	0·01	<0·001

B, standardised regression estimate; *r*-squared = 0·737.

cognitive impairment progressing into Alzheimer's disease[30]. Brain regions such as the hippocampus, neocortex and temporal lobe play a crucial role in episodic memory. Interestingly, the hippocampus accumulates more L + Z relative to other carotenoids[29,31]. A recent cross-sectional analysis of older US adults also identified dietary intakes of L + Z to be positively associated with a measure of immediate and delayed word recall[9]. Thus, L + Z may play an important role in preserving episodic memory during aging. The mechanisms by which L + Z elicits cognitive benefits remain poorly understood, but there is evidence to suggest that L + Z function as dietary antioxidants. Reducing oxidative stress by acting as ROS scavengers may prevent subsequent neuroinflammation, attenuating cognitive decline[5,32].

The average US adult consumes approximately 1–2 mg/d of L + Z[16]. Previous L + Z supplementation trials have utilised approximately 10–12 mg/d of L + Z to elicit cognitive benefits[12–15]. In our sample, cognitive performance was significantly higher in quartiles 3 and 4, which had a mean daily L + Z intake of 2·4 and 5·5 mg, respectively, which is well below that used in supplementation studies but higher than average US intake. Therefore, a supply of L + Z needed to elicit cognitive benefits may be achievable through dietary intake. In our sample, leafy vegetables, cruciferous vegetables, dark yellow vegetables, other vegetables, eggs and fruits were significantly associated with total L + Z intake. Similarly, in a sample of healthy adults, 75 % of L + Z intake was from vegetables, while egg and fruit consumption provided substantially low L + Z to the diet, at only 10 and 4 %, respectively[33]. Furthermore, green vegetables were the primary contributors, followed by white/yellow and red/orange vegetables[33]. Longitudinal studies have demonstrated a relationship between higher vegetable consumption and a reduced risk of cognitive decline in older adults[34–36]. While these studies did not examine L + Z specifically, vegetables are a significant contributor to dietary L + Z intake and, therefore, may play a role in cognitive performance. Fish and seafood intake was also associated with L + Z accumulation in our sample. Although not a significant source of L + Z[37], fish and seafood are rich sources of the carotenoid astaxanthin and EPA and DHA – *n*-3 fatty acids known for their neuroprotective properties[38,39].

Strengths of this study include the analysis of a recent and representative sample of the older US population. A limitation was reliance on self-reported dietary L + Z intake, which may not have accurately reflected the bioavailability and bioactivity of these xanthophylls. Evidence is mixed on the association between intakes of specific L + Z-containing foods and serum and retinal concentrations[33,40–42]. Further, we cannot discount the possibility that the cognitive benefits associated with L + Z intake have been due to an overall healthy dietary pattern. In our analysis, associating L + Z intake with food groups suggested that L + Z could be a possible marker of a plant-based dietary pattern that is high in fruits, vegetables, whole grains and lean proteins and low in red meat and saturated fat. Similar dietary patterns, such as the Mediterranean diet and DASH diet, have been demonstrated to reduce the risk of cognitive decline and/or dementia[43]. Although a high L + Z intake was reflective of a healthier diet pattern, L + Z may have a significant and unique role in cognitive health. Our study supports the growing body of observational, interventional and mechanistic evidence on the neuroprotective properties of L + Z. However, cognitive benefits directly attributable to L + Z as part of an overall healthy dietary pattern requires further study. Additionally, this sample of community-dwelling older adults limits the generalisability of our findings by excluding institutionalised older adults who are at a greater risk of cognitive impairment or decline. Although a cross-sectional analysis was conducted, the HRS is a prospective follow-up study, and additional data will be available in the future to examine the association between L + Z intake and cognitive decline or development of neurodegenerative disease. Further research is needed to examine the association between L + Z intake and cognitive domains other than working

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memory. The HRS administers all cognitive assessments only to adults ≥65 years of age, preventing us from examining the role of L + Z intake in global cognitive function and alternate cognitive subdomains when analysing the complete HCNS sample.

Conclusion

As more evidence suggests that a healthy dietary pattern can benefit cognitive function, observing the role that specific nutrients have on improving cognitive health is imperative for determining the potential to delay cognitive impairment. L + Z is a prevalent carotenoid in the adult brain[3,44], and our findings contribute to the growing literature on the positive relationship between L + Z intake and cognitive health in older adults[13,28,45]. Older adults may benefit from a higher intake of assorted vegetables, fruits and eggs, as L + Z may play a role in delaying cognitive decline, specifically protecting episodic memory. Further research is needed to better understand the mechanism and relationship of L + Z with cognitive function.

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