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Cognitive performance among the elderly in relation to the intake of plant foods. The Hordaland Health Study

Eha Nurk[1,2], Helga Refsum[1,3], Christian A. Drevon[1], Grethe S. Tell[4], Harald A. Nygaard[4,5], Knut Engedal[6] and A. David Smith[3]*

[1]*Department of Nutrition, Institute of Basic Medical Sciences, Faculty of Medicine, University of Oslo, Oslo, Norway*
[2]*Department of Surveillance and Evaluation, National Institute for Health Development, Tallinn, Estonia*
[3]*Department of Physiology, Anatomy and Genetics and the Oxford Project to Investigate Memory and Ageing (OPTIMA), University of Oxford, Oxford, UK*
[4]*Department of Public Health and Primary Health Care, University of Bergen, Bergen, Norway*
[5]*NKS Olaviken Hospital for Old Age Psychiatry, Erdal, Norway*
[6]*Department of Geriatric Medicine, Norwegian Centre for Dementia Research, Oslo University Hospital, Oslo, Norway*

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Fruits and vegetables are among the most nutritious and healthy of foods, and are related to the prevention of many chronic diseases. The aim of the study was to examine the relationship between intake of different plant foods and cognitive performance in elderly individuals in a cross-sectional study. Two thousand and thirty-one elderly subjects (aged 70–74 years; 55 % women) recruited from the general population in Western Norway underwent extensive cognitive testing and completed a comprehensive FFQ. The cognitive test battery covered several domains (Kendrick Object Learning Test, Trail Making Test – part A, modified versions of the Digit Symbol Test, Block Design, Mini-Mental State Examination and Controlled Oral Word Association Test). A validated and self-reported FFQ was used to assess habitual food intake. Subjects with intakes of > 10th percentile of fruits, vegetables, grain products and mushrooms performed significantly better in cognitive tests than those with very low or no intake. The associations were strongest between cognition and the combined intake of fruits and vegetables, with a marked dose-dependent relationship up to about 500 g/d. The dose-related increase of intakes of grain products and potatoes reached a plateau at about 100–150 g/d, levelling off or decreasing thereafter, whereas the associations were linear for mushrooms. For individual plant foods, the positive cognitive associations of carrots, cruciferous vegetables, citrus fruits and high-fibre bread were most pronounced. The only negative cognitive association was with increased intake of white bread. In the elderly, a diet rich in plant foods is associated with better performance in several cognitive abilities in a dose-dependent manner.

Cognitive performance: Fruits: Vegetables: Grain products

There is strong evidence for the importance of fruits and vegetables in our diet. The greater the quantity and assortment of fruits and vegetables consumed, the lower the occurrence of CVD and cancer(1–6), and probably also of chronic obstructive pulmonary disease, asthma and type 2 diabetes(7–9). Moreover, the vegetarian diet shows a strong association with longevity in humans(1,10).

Plant foods are extremely complex and in spite of extensive efforts to identify their composition, the exact structures of the majority of nutrient compounds are not precisely known. However, it is acknowledged that fruits and vegetables are rich in antioxidants and bioactive compounds that may reduce disease risk stemming from reactive oxygen species(11) and are also associated with cognitive benefits(12,13). In addition, a diet high in plant foods may also act on cognition through cerebrovascular mechanisms(14).

Based on animal models it has been suggested that fruit and vegetable supplements high in antioxidant activity may maximise neuronal and cognitive functioning in old age(13,15). Subjects with a greater intake of fruits and vegetables had better cognitive test scores(16–20), and in two large longitudinal studies, a high consumption of vegetables was associated with a slower rate of cognitive decline(12,21). Among Swedish twins, midlife consumption of fruits and vegetables in medium or great amounts compared with no or small consumption was associated with a reduced risk of dementia and Alzheimer's disease approximately 30 years later(22). In the Whitehall II Study(20), those consuming fruits and vegetables less than

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Abbreviations: HADS-A, Hospital Anxiety and Depression Scale anxiety subscale; HADS-D, Hospital Anxiety and Depression Scale depression subscale; HUSK, Hordaland Health Study; KOLT, Kendrick Object Learning Test; m-BD, Block Design short form; m-DST, modified version of Digit Symbol Test; m-MMSE, modified version of the Mini-Mental State Examination; S-task, abridged version of Controlled Oral Word Association Test; tHcy, total homocysteine; TMT-A, Trail Making Test part A.

* **Corresponding author:** Professor A. David Smith, fax +44 1865 272420, email david.smith@pharm.ox.ac.uk

twice per d had a higher risk of poor executive function and memory, with a stronger association seen with consumption measured closest to the time of cognitive assessment over a period as long as 17 years earlier.

The aim of the present study was to examine the relationship of habitual intake, during the previous year, of increasing amounts of fruits, vegetables, potatoes, grain products, mushrooms and nuts to performance in several different cognitive tests. A subset of elderly subjects within the Hordaland Health Study (HUSK) afforded us the opportunity to examine these issues among more than 2000 older men and women. We aimed to examine if the intake of different plant foods showed a dose–response relationship to the cognitive test scores.

Methods

Study population

The HUSK was conducted from 1997 to 1999 as a collaborative effort between the University of Bergen, University of Oslo, local health services and the Norwegian Institute of Public Health. Details of the study and of recruitment to the cognitive sub-study are described elsewhere[23,24]. Briefly, a total of 2841 subjects out of 3341 attendees in the HUSK born in 1925–7 were invited to participate in cognitive tests; 2197 (77·3 %) of these agreed and constitute the cognitive sub-study. In the present report, we have confined the cross-sectional analysis to 2031 (71·5 %) individuals who also completed a FFQ.

The present study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects were approved by the Regional Committee for Medical Research Ethics of Western Norway. Written informed consent was obtained from all subjects.

Data collection

Cognitive testing. This was performed at the study location by trained nurses after the standard cardiovascular examinations of the National Health Screening Service[25] were completed. The cognitive test battery included six tests[26]: the Kendrick Object Learning Test (KOLT, episodic memory)[27]; the Trail Making Test, part A (TMT-A, executive function)[28]; a modified version of the Digit Symbol Test (m-DST, perceptual speed and executive function)[29]; the short form of Block Design (m-BD, visuo-spatial skills)[29]; a modified version of the Mini-Mental State Examination (m-MMSE, global cognition)[30]; and an abridged version of the Controlled Oral Word Association Test, also called ‘S-task’ (access to semantic memory)[31]. For all cognitive tests the higher scores indicate better performance, except TMT-A where the speed of fulfilment is important, i.e. the shorter time used, the better the results (the test score is equal to time in seconds that was used to complete the test).

Dietary habits. To asses habitual food consumption, a comprehensive FFQ created at the Department of Nutrition, University of Oslo was handed out on the day of examination, filled out later at home by the participants and then mailed to the HUSK Project Centre in Bergen. The FFQ has been validated in previous studies[32,33]. The questionnaire included 169 food items that were grouped according to Norwegian meal patterns. It was designed to obtain information on usual food intake during the previous year. The frequency of consumption was given per d, week or month. The portion sizes were given as household measures or units, such as slices, pieces, florets, strips, bunches and handfuls.

Dichotomous variables were created considering individuals who reported use of each particular item, whereas subjects reporting no consumption of the actual product were considered non-users. The amount of each item in g/d or ml/d and total energy intake in kJ/d, as well as total intake of macronutrients and some subgroups of macronutrients in g/d were calculated by using a food database and software system developed at the Department of Nutrition, University of Oslo (KOSTBEREGNINGS-SYSTEM, version 3.2; University of Oslo, Oslo, Norway).

Covariates. The FFQ also included questions about dietary supplement intake, in which the product names of the most used supplements in Norway were considered. Use of dietary supplements was considered as ‘seasonal use’ (during the whole year or only winter half of the year). Intake of vitamin supplements such as multivitamins, folic acid, and vitamins B, C, D and E were all significantly correlated with cognitive test scores and with different intakes of various fruits and vegetables (data not shown). Thus, in our present paper, the use of all these vitamin supplements was combined into one variable.

Self-reported information on diabetes and history of myocardial infarction, angina pectoris, stroke, and hypertension was recorded in 1997–9, and in 1992–3, in addition, history of thrombosis and phlebitis was recorded. On the basis of the information from both surveys, the subjects were categorised as with or without a history of CVD (including the diseases and conditions mentioned above). About four-fifths (79 %) of self-reported CVD cases were validated with hospitalisation records used in our earlier study[34], whereas the remaining 21 % of CVD cases were presumably less severe and did not require hospitalisation or occurred before 1992.

Non-fasting EDTA blood samples were collected for determination of total homocysteine (tHcy) and folate. Plasma tHcy was determined using a fully automated HPLC assay[35] and concentrations of folate were measured by *Lactobacillus casei* microbiological assay[36].

Educational level was self-reported and recorded in five categories: (1) primary school ($\leq$9 years of education); (2) vocational secondary school (10–12 years of education); (3) theoretical secondary school (10–12 years of education); (4) college or university $\leq$ 4 years; and (5) university of $\geq$ 4 years. Smoking was considered in three categories: non-smokers; ex-smokers; and current smokers (including daily smoking of cigarettes, cigars, cigarillos or pipe).

Depression was assessed by using the Hospital Anxiety and Depression Scale[37] – a self-administered questionnaire consisting of fourteen items: seven for anxiety (HADS-A subscale) and seven for depression (HADS-D subscale). The HADS-A and HADS-D are intercorrelated, most often in the range of 0·50 to 0·60[38]. Hence, to identify a more homogeneous group with depression, restrictions were put on the other subscale when cases were defined. Thus, depression was defined as a HADS-D score of 8 or more restricted to a HADS-A score less than 8.

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Statistical analysis

Because the numbers of participants reporting no intake of any type of fruits or vegetables, potatoes and grain products were very small, the cut-off points for low intakes of these groups were set at the 10th percentile. Preliminary analyses showed that cognitive test scores and intake of various plant foods were significantly associated with one or more of the following variables: sex; education; vitamin supplement use (multivitamins, folic acid, vitamins B, C, D or E); smoking status; history of CVD; diabetes; intakes of dairy products, meat, fish, total fat and protein (data not shown). Thus, the final fully adjusted models, used throughout the present paper, were controlled for all these variables. Due to potential over-adjustment we have selected both a simple (sex-adjusted) model and a fully adjusted model in the tables presenting mean intakes and linear associations. Given the narrow age range, adjustment for age did not change the results and has not been included.

Estimated mean values of cognitive scores by intake of different plant foods adjusted for sex and also *P* values adjusted according to our final model of cofactors were obtained from the univariate ANOVA. Multiple linear regression analyses adjusted for the same variables were used to examine the relationship between cognitive test scores and dietary intake of individual plant food items. Gaussian generalised additive regression models, as implemented in S-PLUS 6.2 for Windows (Insightful Corp., Seattle, WA, USA), were used to generate graphic representations of the dose–response relationships, using a sex-adjusted model. On the vertical axis, the model generates a reference value of zero that approximately corresponds to the value of cognitive test score associated with the mean of the average intake of fruits or vegetables in g/d for all subjects. Multiple linear regression analyses were used to examine significant associations between the cognitive test scores and average of plant foods intake using both a sex-adjusted model and a model adjusted for the variables referred to in the final model. Except for generalised additive models, all statistical analyses were performed using the Statistical Package for the Social Sciences version 12.0 for Windows (SPSS, Inc., Chicago, IL, USA). $P<0.05$ was considered significant.

Results

Mean intakes of different plant foods among the 2031 participants and among users (those who at least once per month consumed a particular item) of each group are presented in Table 1. Total intake of fruits and vegetables was more than 400 g/d, where fruit intake was about 240 g/d and intake of

Table 1. Mean intakes of different plant foods of 2031 elderly participants in the cognitive sub-study of the Hordaland Health Study

(Mean values and 95 % confidence intervals)

	All participants		Consumers*		
	Mean	95 % CI	Consumers (*n*)	Mean	95 % CI
Combined fruits and vegetables (g/d)	426	415, 437	2023	428	417, 439
Fruits (g/d)	240	232, 247	2016	242	234, 249
Citrus fruits (g/d)	40	38, 43	1563	52	49, 55
Apples (g/d)	48	45, 50	1742	56	53, 58
Other fresh fruits (g/d)	45	43, 47	1790	51	48, 53
Berries (g/d)	4·8	4·2, 5·3	940	10	9, 11
Orange juice (ml/d)	42	38, 46	1011	85	78, 91
Other juices (ml/d)	10	9, 11	439	47	40, 54
Conserved fruits and berries (g/d)	30	29, 31	1825	33	32, 35
Vegetables (g/d)	186	180, 192	2007	188	183, 194
Carrots (g/d)	47	45, 48	1852	51	49, 53
Rutabaga (g/d)	18	16, 19	1471	24	23, 26
Cabbage (g/d)	5·4	5·0, 5·8	1260	8·7	8·2, 9·3
Cauliflower, broccoli and Brussels sprouts (g/d)	30	28, 31	1620	37	35, 39
Onion (g/d)	4·3	4·0, 4·5	1392	6·2	5·9, 6·6
Lettuce (g/d)	2·1	1·9, 2·3	992	4·3	4·0, 4·6
Cucumber (g/d)	3·1	2·8, 3·3	958	6·5	6·1, 7·0
Tomatoes (g/d)	20	19, 21	1619	25	24, 26
Red bell pepper (g/d)	3·8	3·5, 4·1	1162	6·7	6·2, 7·1
Green cabbage and spinach (g/d)	9·4	8·2, 10·7	582	33	29, 37
Legumes (g/d)	1·3	1·3, 1·4	1507	1·8	1·7, 1·9
Potatoes (g/d)	129	126, 132	1977	133	129, 136
Grain products (g/d)	186	182, 189	2025	186	183, 189
White bread (g/d)	13	12, 14	563	47	44, 50
Medium-fibre bread (g/d)	41	39, 44	860	97	94, 101
High-fibre bread (g/d)	100	97, 104	1428	143	139, 146
Flour, rice and pasta (g/d)	9·1	8·7, 9·6	1941	9·5	9·1, 10
Breakfast cereals (g/d)	11	10, 12	1244	18	17, 19
Cakes, pies and cookies (g/d)	30	28, 31	1818	33	31, 35
Mushrooms (g/d)	2·9	2·5, 3·4	501	12	10, 14
Nuts (g/d)	0·7	0·6, 0·9	320	4·6	3·9, 5·4

* Refers to those who consumed the particular item at least once per month.

vegetables close to 190 g/d. Carrot was the most preferred vegetable with a daily intake of about 50 g; 91 % of participants consumed carrots. The intakes of different types of fruits were similar (both the daily intake and percentage of consumers), whereas less than half (46 %) reported intake of berries. Consumption of orange juice was more popular than other juices. The majority of participants reported consumption of potatoes (97 %), with a daily intake of about 130 g. Intake of grain products was 186 g/d, from which about three-quarters was intake of high-fibre bread (143 g/d). About 25 % of the study population reported intake of mushrooms and only 16 % consumed nuts.

Compared with other individuals participating in the HUSK but not in the cognitive sub-study, the participants in the latter study consumed significantly more fruits, vegetables, mushrooms and nuts than non-participants: mean intake of fruits was 235 (95 % CI 228, 242) *v.* 210 (95 % CI 201, 220) g/d ($P<0{\cdot}001$); mean intake of vegetables was 186 (95 % CI 180, 192) *v.* 162 (95 % CI 154, 170) g/d ($P<0{\cdot}001$); mean intake of mushrooms was 2·9 (95 % CI 2·5, 3·4) *v.* 1·8 (95 % CI 1·4, 2·2) g/d ($P=0{\cdot}002$); mean intake of nuts was 0·5 (95 % CI 0·4, 0·6) *v.* 0·3 (95 % CI 0·3, 0·4) g/d ($P=0{\cdot}003$). The differences in intakes of potatoes and grain products were only 2 g/d ($P=0{\cdot}52$) and 3 g/d ($P=0{\cdot}25$), respectively.

Men consumed more potatoes, grain products and nuts than women (Table 2). Higher education (>9 years) was related to higher intake of all main groups of plant foods. Participants without CVD history consumed more vegetables than CVD patients and participants without diabetes ate more fruits and potatoes, and less grain products than diabetics. Smokers consumed less fruits than non-smokers and vitamin supplement users ate more fruits, vegetables and mushrooms than non-users. Participants with depression ate less fruits and vegetables than those without.

Mean intakes of total energy, macronutrients, some subgroups of macronutrients and main groups of non-plant foods by quartiles of main groups of plant foods are presented in Supplemental Table 1S (available online) under 'Supplemental data'.

The performance on all six cognitive tests was better among consumers of fruits, vegetables and mushrooms than among non-consumers (Table 3). These associations remained significant for vegetables and for the combined group of fruits and vegetables (except m-BD), and for fruits (except TMT-A) after adjustment for sex, education, vitamin supplement use (multivitamins, folic acid, vitamins B, C, D or E), smoking status, history of CVD, diabetes, and intakes of dairy products, meat, fish, total fat and protein. For intakes of mushrooms and grain products, the associations with three or four cognitive tests remained significant after multivariable adjustment. The mean scores of all six cognitive tests (except TMT-A) were better among potato eaters as compared with non-eaters, but except for the m-MMSE, the associations were no longer significant in the multiple adjusted models. Nut consumption was associated with better test scores only in the sex-adjusted models for TMT-A, m-DST and S-task.

The performance on all cognitive tests improved with increasing intake of fruits and vegetables; the strongest association was up to about 500 g/d (Fig. 1). The favourable association of vegetable intake alone reached a maximum at a dose of about 150–200 g/d. Similarly, increasing cognitive performance with increasing intakes of potatoes or grain products reached a plateau or started to decrease at about 100–150 g/d. The dose–response associations of fruits and mushrooms on cognitive performance tended to be linear. Linear regression analyses adjusted only for sex indicated that the dose–response associations with fruits and vegetables were significant for each of the cognitive tests, except for the association between fruits and TMT-A. In the fully adjusted models the relationships between combined fruits and vegetables and TMT-A and m-MMSE disappeared. When fruits and vegetables were analysed separately, associations between fruits and KOLT, m-BD and S-task, and between vegetables and TMT-A, m-DST, m-MMSE and S-task, remained significant after controlling for multiple covariates. Most of the associations related to mushroom intake were significant (TMT-A, m-BD, m-DST, and S-task) in sex-adjusted models and the last two also remained significant in the multiple adjusted models. Dose–response relationships between intake of potatoes and KOLT, m-BD and m-MMSE were also significant, but only the latter remained significant in multiple adjusted models. Intake of grain products was not significantly associated with cognitive test scores in the multiple adjusted models. The associations between intake of nuts and cognitive test performance were linear but not statistically significant (data not shown).

The majority of the consumers of different vegetables performed better in cognitive tests as compared with non-consumers (see Supplemental Table 2S, available online). All differences in test scores related to carrot and rutabaga intakes remained significant after multiple adjustments. In addition, consumers of cruciferous vegetables (cabbage, cauliflower, broccoli and Brussels sprouts) performed better in several cognitive tests than non-users, whereas associations with intakes of other types of vegetables were not consistent in different cognitive tests. For intake of fruits, the citrus fruits had the strongest associations with mean test scores. Consumption of high-fibre bread was associated with better test scores in TMT-A, m-DST, m-BD and S-task, whereas most associations with other grain products lost their significance after multiple adjustments.

In simple linear associations (adjusted for sex only), intakes of carrot, lettuce, cucumber, tomato, and red bell pepper were positively related with all cognitive test scores (Table 4). Intake of white bread was negatively and linearly associated with all of the cognitive tests, except S-task. Citrus fruits, other fresh fruits and the combined groups of cauliflower, broccoli and Brussels sprouts, and the combined group of flour, rice and pasta, were positively associated with five out of six cognitive tests, whereas intakes of apples and orange juice were positively associated with four out of six tests. The associations with other items were more random. Adjustment for multiple cofactors reduced the number of significant associations; the strongest relationships with cognitive test performance were with citrus fruits where four out of six tests remained significant (positively) and with white bread where three out of six remained significant (inversely).

After additional adjustment for total vegetable intake in the models concerning associations between total fruit intake and different cognitive tests, all associations remained statistically significant (except the association with TMT-A in Table 3: *P* value changed to 0·07). Similarly, additional adjustment for total fruit intake in the models concerning associations

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Table 2. Characteristics of the study population by intake of main groups of plant foods

(Mean values and 95 % confidence intervals)

		Combined fruits and vegetables		Fruits		Vegetables		Potatoes		Grain products		Mushrooms		Nuts	
	n	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI
Sex															
Men	918	431	415, 447	241	231, 252	190	181, 199	157	153, 162	211	206, 217	3·0	2·5, 3·5	1·0	0·7, 1·2
Women	1113	422	407, 437	239	228, 249	183	175, 191	106***	102, 110	164***	161, 168	2·9	2·2, 3·6	0·5*	0·4, 0·7
Education															
≤ 9 years	802	372	356, 388	215	203, 227	157	149, 165	120	115, 125	182	177, 188	1·3	0·9, 1·7	0·5	0·3, 0·6
> 9 years	1195	468***	454, 483	260***	250, 270	208***	200, 216	137***	132, 141	189*	185, 193	4·1***	3·4, 4·8	0·9*	0·7, 1·1
History of CVD															
Yes	661	409	390, 429	231	217, 246	178	168, 188	127	121, 133	186	180, 192	2·4	1·8, 2·9	0·8	0·5, 1·1
No	1313	437*	424, 451	245	236, 254	192*	185, 200	131	127, 135	187	183, 191	3·1	2·6, 3·7	0·7	0·6, 0·9
Diabetes															
Yes	126	389	349, 429	198	173, 224	191	167, 215	112	101, 124	209	194, 224	2·8	1·2, 4·4	0·6	0·2, 0·9
No	1868	428	417, 440	242*	234, 250	186	180, 192	131*	127, 134	184***	181, 188	2·9	2·4, 3·3	0·7	0·6, 0·9
Current smoking															
Yes	268	408	376, 441	217	195, 240	191	173, 209	126	118, 135	178	170, 187	3·6	2·2, 5·0	0·5	0·3, 0·7
No	1763	429	417, 440	243*	235, 251	186	179, 192	130	126, 133	187	183, 190	2·8	2·4, 3·3	0·8	0·6, 0·9
Vitamin supplement intake†															
Yes	695	471	454, 489	263	250, 275	209	199, 218	132	127, 138	187	182, 192	3·6	2·8, 4·4	0·8	0·6, 1·0
No	1336	403***	389, 416	228***	218, 237	175***	167, 182	127	123, 132	185	181, 189	2·6*	2·0, 3·1	0·7	0·5, 0·9
Depression‡															
Yes	172	377	340, 413	212	187, 236	165	144, 187	133	121, 145	182	170, 194	1·9	1·0, 2·8	0·9	0·5, 1·4
No	1707	440*	428, 452	248*	240, 256	192*	186, 199	130	127, 134	188	184, 191	3·0	2·6, 3·5	0·7	0·6, 0·9

* $P < 0·05$, *** $P < 0·001$.

† Use of multivitamins, folic acid, vitamins B, C, D or E.

‡ Hospital Anxiety and Depression Scale score ≥ 8.

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between total vegetable intake and different cognitive tests did not affect the results (except the association with S-task in Fig. 1: *P* value changed to 0·10). When associations between intakes of potatoes, grain products, mushrooms, nuts and different cognitive tests were additionally adjusted for total fruit and vegetable intake, the only association that lost its significance was between intake of mushrooms and S-task in Fig. 1 (*P* value changed to 0·15). Further adjustment for plasma concentrations of tHcy and folate in the models concerning associations between all main groups of plant foods and cognitive test performance did not affect the significant results, except for the association between vegetables and m-MMSE in Fig. 1 (*P* value changed to 0·06).

About three-quarters of significant associations in Supplemental Table 2S (forty-four out of fifty-eight) remained significant after additional adjustment for total intake of fruits and vegetables, and plasma concentrations of tHcy and folate. In Table 4, one-third of the significant associations remained after further adjustment for total intake of fruits and vegetables, and plasma tHcy and folate.

Although depression was significantly correlated with cognitive test performance and with intake of fruit and vegetables, inclusion of depression score as a covariate in statistical models weakened the associations only marginally, i.e. all strong associations ($P < 0·01$) remained significant (data not shown).

Table 3. Cognitive test scores by intake of main groups of plant foods
(Mean values and 95 % confidence intervals)

		High intake			Low intake or non-users				
Main groups (cut-off for low intake*)	Cognitive test	Total *n*	Mean	95 % CI	Total *n*	Mean	95 % CI	*P*†	*P*‡
Combined fruits and vegetables (≤144 g/d)	KOLT	1826	35·7	35·3, 36·0	201	32·7	31·6, 33·8	<0·001	0·008
	TMT-A	1824	55·1	53·5, 56·6	200	65·9	61·4, 70·5	<0·001	0·003
	m-DST	1822	10·5	10·3, 10·7	200	8·6	8·0, 9·2	<0·001	0·006
	m-BD	1820	15·1	15·0, 15·2	198	14·5	14·1, 14·8	<0·001	0·06
	m-MMSE	1811	11·6	11·5, 11·6	199	11·3	11·1, 11·4	<0·001	<0·001
	S-task	1824	15·4	15·2, 15·7	200	13·0	12·3, 13·8	<0·001	0·001
Fruits (≤60 g/d)	KOLT	1823	35·6	35·2, 36·0	204	33·3	32·2, 34·4	<0·001	0·026
	TMT-A	1820	55·4	53·9, 56·9	204	62·5	57·9, 67·0	0·004	0·053
	m-DST	1818	10·5	10·3, 10·7	204	9·0	8·4, 9·6	<0·001	0·019
	m-BD	1815	15·1	15·0, 15·2	203	14·5	14·2, 14·8	0·001	0·030
	m-MMSE	1808	11·5	11·5, 11·6	202	11·3	11·2, 11·4	<0·001	0·004
	S-task	1820	15·3	15·1, 15·6	204	13·7	12·9, 14·4	<0·001	0·018
Vegetables (≤44 g/d)	KOLT	1824	35·6	35·3, 36·0	203	32·8	31·7, 33·9	<0·001	0·010
	TMT-A	1822	55·1	53·6, 56·6	202	65·4	60·8, 70·0	<0·001	0·005
	m-DST	1820	10·5	10·3, 10·7	202	8·7	8·2, 9·3	<0·001	0·025
	m-BD	1819	15·1	15·0, 15·2	199	14·5	14·2, 14·8	<0·001	0·07
	m-MMSE	1810	11·6	11·5, 11·6	200	11·3	11·1, 11·4	<0·001	<0·001
	S-task	1822	15·4	15·2, 15·7	202	13·1	12·3, 13·8	<0·001	0·016
Potatoes (≤46 g/d)	KOLT	1816	35·6	35·2, 35·9	211	33·7	32·6, 34·8	0·002	0·21
	TMT-A	1814	55·8	54·3, 57·3	210	59·1	54·6, 63·7	0·17	0·58
	m-DST	1812	10·5	10·3, 10·7	210	9·2	8·7, 9·8	<0·001	0·22
	m-BD	1809	15·1	15·0, 15·2	209	14·7	14·4, 15·0	0·013	0·36
	m-MMSE	1801	11·6	11·5, 11·6	209	11·2	11·1, 11·4	<0·001	<0·001
	S-task	1814	15·3	15·1, 15·6	210	13·9	13·2, 14·7	0·001	0·50
Grain products (≤101 g/d)	KOLT	1826	35·5	35·1, 35·9	201	34·1	33·0, 35·2	0·018	0·033
	TMT-A	1824	55·8	54·2, 57·3	200	59·5	54·9, 64·1	0·13	0·031
	m-DST	1822	10·4	10·2, 10·6	200	9·9	9·3, 10·5	0·12	0·37
	m-BD	1819	15·1	15·0, 15·2	199	14·8	14·4, 15·1	0·07	0·44
	m-MMSE	1811	11·5	11·5, 11·6	199	11·4	11·3, 11·5	0·006	0·029
	S-task	1824	15·2	15·0, 15·5	200	14·6	13·8, 15·4	0·13	0·29
Mushrooms	KOLT	500	37·0	36·3, 37·7	1527	34·8	34·4, 35·2	<0·001	0·001
	TMT-A	499	49·3	46·5, 52·2	1525	58·4	56·7, 60·0	<0·001	0·013
	m-DST	499	12·0	11·6, 12·3	1523	9·8	9·6, 10·0	<0·001	<0·001
	m-BD	498	15·3	15·1, 15·5	1520	14·9	14·8, 15·1	0·004	0·43
	m-MMSE	499	11·7	11·6, 11·7	1511	11·5	11·4, 11·5	<0·001	0·17
	S-task	499	17·0	16·5, 17·5	1525	14·6	14·3, 14·8	<0·001	<0·001
Nuts	KOLT	320	35·9	35·0, 36·8	1707	35·3	34·9, 35·6	0·18	0·80
	TMT-A	320	52·2	48·6, 55·8	1704	56·9	55·3, 58·4	0·021	0·27
	m-DST	319	10·9	10·5, 11·4	1703	10·2	10·0, 10·4	0·006	0·82
	m-BD	320	15·2	14·9, 15·4	1698	15·0	14·9, 15·1	0·26	0·54
	m-MMSE	318	11·6	11·5, 11·6	1692	11·5	11·5, 11·6	0·37	0·39
	S-task	320	15·9	15·3, 16·5	1704	15·0	14·8, 15·3	0·009	0·81

KOLT, Kendrick Object Learning Test; TMT-A, part A of the Trail Making Test; m-DST, modified version of the Digit Symbol Test; m-BD, modified version of Block Design; m-MMSE, modified version of the Mini Mental State Examination; S-task, abridged version of the Controlled Oral Word Association Test.

* Cut-off points are shown for low intake and were set at the 10th percentile, except for mushrooms and nuts where cut-off of 0 g/d was considered.

† ANOVA, adjusted for sex.

‡ ANOVA adjusted for sex, education, vitamin supplement use (multivitamins, folic acid, vitamins B, C, D or E), smoking status, history of CVD, diabetes, intakes of dairy products, meat, fish, total fat and protein.

Discussion

In a population-based study of elderly individuals, we have shown that habitual intake of several types of plant food is associated with better performance in several cognitive domains. The associations were dose-dependent and applied to most cognitive tests used in the study.

Consistent with the present study, associations between greater intake of fruits and vegetables and better cognitive performance have been observed in cross-sectional studies[16,18,19]. In longitudinal studies, higher intake of vegetables has been reported to be inversely associated with cognitive decline, whereas there has been no significant

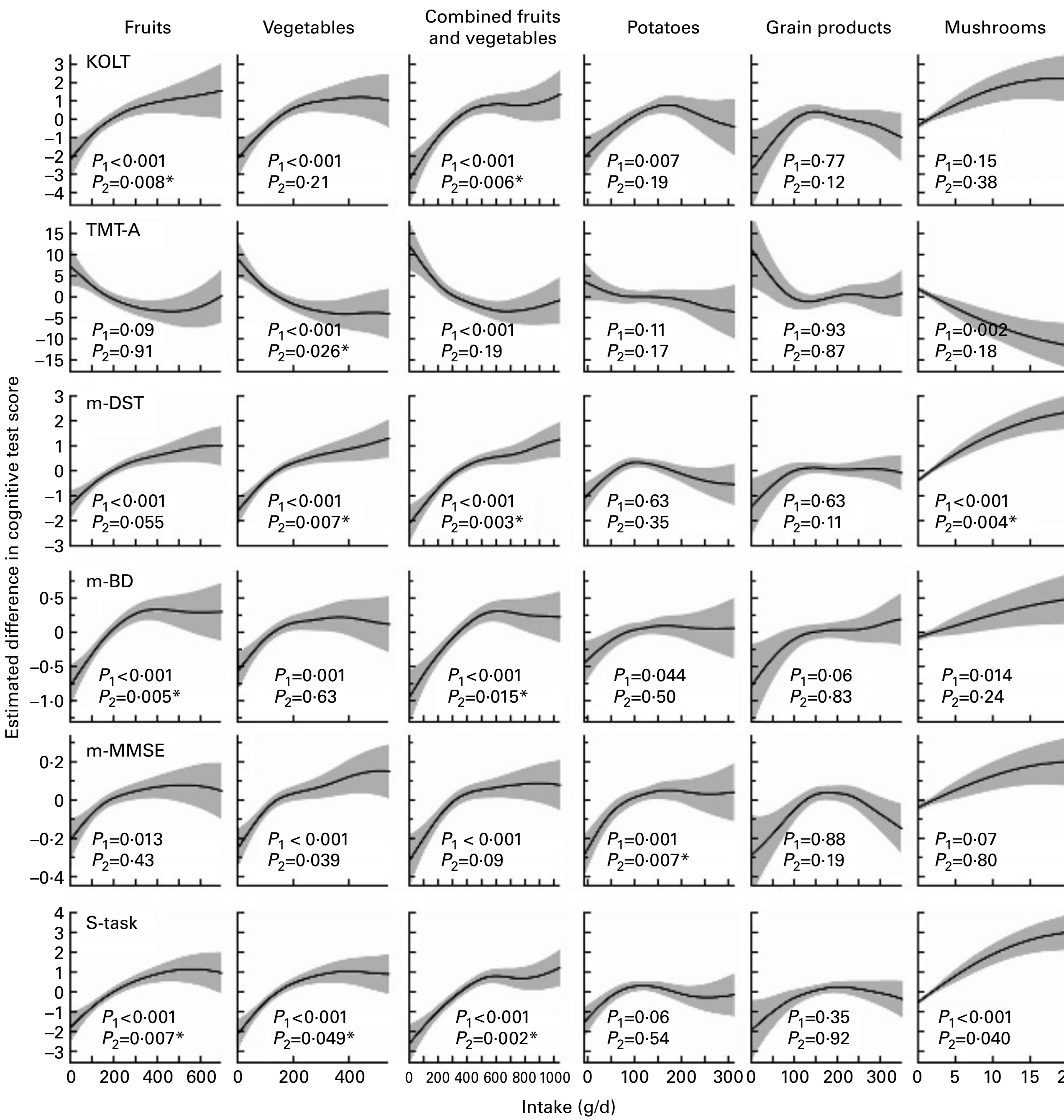

Fig. 1. Associations between different cognitive test scores and intake of fruits, vegetables, potatoes, grain products and mushrooms obtained by Gaussian generalised additive regression models. Solid lines are the estimated dose–response curves; shaded areas represent the 95 % CI. Linear regression coefficients and *P* values are from corresponding multiple linear regression analyses. P_1 values are adjusted for sex and P_2 values are adjusted for sex, education, vitamin supplement use (multivitamins, folic acid, vitamins B, C, D or E), smoking status, history of CVD, diabetes, intakes of dairy products, meat, fish, total fat and protein. The data for the highest 2·5 percentiles of all intakes of plant foods are not included. KOLT, Kendrick Object Learning Test; TMT-A, part A of the Trail Making Test; m-DST, modified version of the Digit Symbol Test; m-BD, modified version of Block Design; m-MMSE, modified version of the Mini Mental State Examination; S-task, abridged version of the Controlled Oral Word Association Test. *$P<0·05$, Linear regression analyses, adjusted in addition to total intake of fruits and vegetables and plasma concentrations of total homocysteine and folate.

Table 4. Linear regression coefficients (adjusted for sex) for cognitive test scores by intake of different types of plant foods (g/d)

	KOLT		TMT-A		m-DST		m-BD		m-MMSE		S-task	
	β	*P*	β	*P*	β	*P*	β	*P*	β	*P*	β	*P*
Citrus fruits	0·074	0·001*	−0·055	0·014*	0·090	<0·001*†	0·072	0·001*	0·057	0·011	0·035	0·12
Apples	0·088	<0·001*	−0·046	0·037	0·046	0·040	0·061	0·006	0·027	0·23	0·041	0·06
Other fresh fruits	0·054	0·013	−0·020	0·37	0·073	0·001	0·050	0·025	0·066	0·003*	0·070	0·002
Berries	0·031	0·15	0·015	0·49	0·009	0·70	0·028	0·21	0·001	0·96	0·044	0·047
Orange juice	0·057	0·009	−0·036	0·11	0·097	<0·001	0·079	<0·001*	0·020	0·36	0·136	<0·001*†
Other juices	−0·020	0·36	0·066	0·003*†	−0·012	0·60	−0·029	0·20	−0·020	0·37	0·002	0·94
Conserved fruits and berries	0·017	0·44	−0·008	0·71	0·002	0·94	0·060	0·008	0·003	0·90	−0·009	0·69
Carrots	0·067	0·002	−0·080	<0·001*†	0·098	<0·001*	0·057	0·010	0·064	0·004	0·069	0·002
Rutabaga	0·022	0·32	−0·080	<0·001	−0·006	0·77	−0·002	0·92	0·010	0·66	−0·007	0·74
Cabbage	0·038	0·08	−0·017	0·46	−0·002	0·91	0·029	0·20	0·016	0·48	0·038	0·09
Cauliflower, broccoli and Brussels sprouts	0·061	0·005	−0·061	0·006	0·127	<0·001	0·035	0·11	0·088	<0·001	0·105	<0·001
Onion	0·033	0·14	−0·022	0·32	0·039	0·08	0·003	0·90	0·013	0·57	0·046	0·038
Lettuce	0·072	0·001	−0·089	<0·001*	0·148	<0·001*	0·063	0·005	0·054	0·015	0·096	<0·001
Cucumber	0·075	0·001	−0·095	<0·001*	0·152	<0·001*†	0·062	0·005	0·058	0·009	0·097	<0·001
Tomatoes	0·057	0·009	−0·083	<0·001*†	0·111	<0·001*	0·065	0·004	0·079	<0·001	0·102	<0·001
Red bell pepper	0·087	<0·001	−0·098	<0·001*	0·165	<0·001*	0·048	0·033	0·074	0·001	0·134	<0·001
Green cabbage and spinach	0·003	0·89	−0·033	0·14	0·052	0·019	0·007	0·76	0·041	0·07	0·050	0·024
Legumes	0·072	0·001	−0·030	0·19	0·038	0·09	0·043	0·054	0·043	0·06	0·050	0·025
White bread	−0·050	0·023*	0·046	0·039	−0·053	0·017*	−0·061	0·006*	−0·053	0·018*†	−0·036	0·11
Medium high-fibre bread	−0·010	0·64	0·017	0·45	−0·051	0·022	0·005	0·82	−0·017	0·44	−0·028	0·21
High-fibre bread	0·002	0·91	−0·012	0·59	0·024	0·29	0·024	0·28	0·011	0·63	0·017	0·44
Flour, rice and pasta	0·048	0·028	−0·034	0·13	0·086	<0·001	0·061	0·007	0·046	0·043	0·057	0·011
Breakfast cereals	0·020	0·37	−0·019	0·38	0·063	0·005	0·060	0·007	0·041	0·07	0·050	0·026
Cakes, pies and cookies	−0·035	0·12*†	0·003	0·90	0·045	0·047	0·048	0·032	0·009	0·70	0·021	0·36

KOLT, Kendrick Object Learning Test; TMT-A, part A of the Trail Making Test; m-DST, modified version of the Digit Symbol Test; m-BD, modified version of Block Design; m-MMSE, modified version of the Mini Mental State Examination; S-task, abridged version of the Controlled Oral Word Association Test.

* $P<0.05$; linear regression analyses after additional adjustment for sex, education, vitamin supplement use (multivitamins, folic acid, vitamins B, C, D or E), smoking status, history of CVD, diabetes, intakes of dairy products, meat, fish, total fat and protein.

† $P<0.05$; linear regression analyses after further adjustment for total intake of fruit and vegetables, and plasma concentrations of total homocysteine and folate.

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association between intake of fruits and cognitive decline[12,21]. In the present study, the associations between intake of fruits and vegetables and cognitive performance differed according to the cognitive domain. Total vegetable consumption had the strongest associations with executive function, perceptual speed, global cognition and semantic memory (TMT-A, m-DST, m-MMSE and S-task). Vegetable consumers compared with non-consumers also had better test scores (without a dose–response association) for episodic memory (KOLT). In contrast, total fruit intake had the most consistent associations with visuo-spatial skills and episodic and semantic memory (m-BD, KOLT and S-task), whereas there was no significant dose–response association (only better test scores) related to executive function, perceptual speed and global cognition (TMT-A, m-DST and m-MMSE). The findings that intake of fruits and vegetables do not always give the same results and are related with different cognitive domains could suggest that the underlying mechanisms may be different. Moreover, additional adjustment for total vegetable or fruit intake in the models where fruits and vegetables were studied separately hardly affected the results in our present study, indicating independent associations of fruits and vegetables on cognitive performance.

In the Chicago Health and Aging Project[21], an inverse association between cognitive decline and intake of all types of vegetables (except legumes) was reported. In the Nurses' Health Study[12], greater intake of cruciferous vegetables and green leafy vegetables was associated with better cognitive performance or less cognitive decline. Consistently, carrot and cruciferous vegetables (rutabaga, cabbage, cauliflower, broccoli and Brussels sprouts) were most frequently associated with better scores in different cognitive tests in our present study. The associations with intake of lettuce were less consistent and legumes were significantly associated only with episodic memory (KOLT). In contrast to animal studies, where dietary supplements with spinach extract have been reported to reduce some neurological deficits in aged animal models[13], we found that intake of spinach and green cabbage in combination was significantly associated only with perceptual speed and executive function (m-DST). Also, intake of onion was weakly associated with cognitive performance; the only significant result was related to better episodic memory (KOLT) score among consumers compared with non-consumers. Intake of tomato, cucumber and red bell pepper was often associated with different cognitive tests and the latter two had the highest linear regression coefficients. In general, we found that several types of vegetable were most frequently associated with episodic memory, executive function and perceptual speed (KOLT, TMT-A and m-DST), and the latter two tests showed the most consistent associations, i.e. both with regard to better test scores and linear associations.

Supplementing a rat's diet with berries has been shown to slow and in some cases even reverse brain dysfunction, motor performance, learning and memory in old animals[13]. The only significant association we observed for berries was with executive function (TMT-A). Among fruits, citrus fruits had the strongest positive association with most cognitive abilities in the present study, whereas apples, other fresh fruits and orange juice exhibited less consistent associations.

Intakes of dietary cereals and grains have been reported to be inversely related to Alzheimer's disease and cognitive impairment[18,39]. Regular consumers of breakfast cereals performed better on memory tests[40], and intake of bread and cereal at least weekly was related to more than 60 % reduced risk on cognitive impairment[41]. In contrast, the relationships between grain products and cognitive performance were rather weak in our present study, as total intake of grain products was only associated with better test results for episodic memory, executive function and global cognition (KOLT, TMT-A and m-MMSE). The weak association may be explained by the fact that the intake of whole-grain products was not specified in most of the categories in the present study. However, we found that consumption of high-fibre bread was associated with better test scores in most cognitive tests, whereas increasing intake of white bread was linearly associated with poorer test scores for episodic memory, perceptual speed, executive function, visuo-spatial skills and global cognition (KOLT, m-DST, m-BD and m-MMSE). White bread consumption has been associated with an unhealthy lifestyle[42,43] and poor diet quality[44]. In addition, whole-grain bread intake has been reported to reduce cardiovascular and cancer death rates among middle-aged Norwegians[42], and among middle-aged Bedouin Arabs white bread intake, as compared with whole-wheat bread intake, was associated with about 10-fold risk of having one or more chronic conditions, such as hypercholesterolaemia, hypertension, type 2 diabetes and chronic heart disease[44]. Because there is no mandatory folic acid fortification of foods in Norway, this may explain the weaker associations of cereals in the present study than in studies performed in the USA[39,41].

The amount of potatoes consumed (about 130 g/d) showed a significant association with cognition in the present study. Despite a high consumption of potatoes in the human diet and its content of high-quality proteins, mineral salts and vitamins, the association of potatoes with cognition appears not to have been reported before. In the present study, we found that intake of potatoes was associated with a significantly better mean test score and a dose–response relationship related to global cognition (m-MMSE).

Although only about one-quarter of the present study population reported consumption of mushrooms, we found that this was strongly positively associated with perceptual speed, executive function and semantic memory (m-DST and S-task) and there were also better test scores related to episodic memory and executive function (KOLT and TMT-A) among mushroom eaters as compared with non-eaters. Recently, in a double-blind placebo-controlled trial, intake of tablets containing 96 % of mushrooms (*Hericium erinaceus*) was effective in improving mild cognitive impairment reversibly[45].

Frequent intake of nuts has been reported to reduce risk for CVD[46,47] and in a population-based Greek study intake of fruits and nuts was inversely related to total mortality[48]. Because nuts and seeds are the important dietary sources of vitamin E, their use may also improve cognitive performance. In our present study nut users had better test scores than non-users, but the associations did not reach the level of statistical significance.

Most of the significant associations in our present study remained significant after additional adjustment for total intake of fruits and vegetables, suggesting that these

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associations are strong and independent. As moderately elevated concentrations of tHcy and/or low-normal blood concentrations or intakes of certain B vitamins (folate, vitamin B_6, and vitamin B_{12}) are associated with an increased risk of brain atrophy and developing cognitive impairment and dementia in the elderly(49), we further adjusted the present results for plasma concentrations of tHcy and folate. The majority of the associations remained significant after this adjustment, indicating that the remaining effect is probably due to factors unrelated to folate.

We can only speculate about the possible biological basis of our findings, as the associations are based only on the results from the FFQ and quantitative estimates of various nutrients were not considered. Moreover, plant foods contain a variety of substances, many of which individually or synergistically might account for the apparent protective effect on cognition. Antioxidants are one candidate(19,50), and we have already shown that in this population intakes of foods rich in flavonoids (in particular tea, wine and chocolate) are related to better cognitive test scores(51). Another candidate is dietary folate, which has been related to homocysteine in cognitive decline during ageing(49). Our previous report showed that the consumption of fruit and vegetables in this population is associated with an increase in plasma folate concentrations(52). It is likely that other factors present in plant foods, in addition to antioxidants and folate, may play a role in brain health, as well as non-plant food, such as fish(26). Moreover, lifestyle variables tend to cluster and increased intake of fruits and vegetables is generally associated with a healthy diet and lifestyle and higher education, which in turn are associated with better cognitive health(53). But as an elderly individual's diet is shaped by a lifelong set of preferences, and may be more consistent as an individual ages than other health behaviours(14), the diet may play a major role in health in old age. On the other hand, cognitive impairment in the elderly itself may be an important factor for dietary changes. In addition to diet and lifestyle there are several other factors that influence cognitive health, such as vascular risk factors, depression, and familial and genetic factors(54).

The strengths of the present study include a large population-based sample with six different cognitive tests and use of a validated FFQ(32,33). However, the present study also has several limitations. Because 77 % of the study attendees volunteered for cognitive testing, the possibility of recruitment bias should be considered. Some differences between those who underwent and those who did not undergo cognitive testing have been reported in our present study and earlier(55).

Cognition in the elderly is shaped by long-term exposures(56,57). Thus, a major limitation of the present study is the cross-sectional design, although the questionnaire focused on food intake during the previous year. Furthermore, subjects with impaired cognition may have altered their diet as a consequence of a change in their cognitive status. In addition, self-reported dietary data collected from subjects who are cognitively impaired or demented may be less reliable. However, because the participants in our present study were not seriously impaired (231 out of 1992 participants who completed all cognitive tests performed poorly in two or more tests, including four individuals who performed poorly in all six tests, nine in five tests, thirty in four tests, sixty-five in three tests and 123 in two tests), we do not believe that this has a major impact on our findings. Last but not least, foods are not consumed individually but as part of a diet and therefore potential residual confounding by other food items is always an issue in studies using dietary assessments.

Conclusion

In a population-based study we have shown that intake of many plant foods is associated with better performance across several cognitive abilities and that the associations are dose-dependent. Thus, in addition to the impact of increasing intake of fruits and vegetables on prevention of CVD and cancer(6), people may also benefit from increased fruit and vegetable intake in their cognitive health. Not all plant foods showed equally positive associations with cognitive performance, indicating that certain items (mainly carrots, cruciferous vegetables, citrus fruits and high-fibre bread) are the most valuable choices. However, a combination of fruits and vegetables had the strongest associations and highest linear regression coefficients in relation to cognitive function, suggesting that cumulative effects of multiple dietary components may be substantial.

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H. R. and G. S. T. participated in the study design and organisation of data collection. K. E., H. A. N. and A. D. S. assisted with the design and organisation of the cognitive sub-study. C. A. D. helped to develop the FFQ. E. N. conducted the statistical analyses and wrote the first draft of the manuscript. All co-authors interpreted the results, contributed to the study design and participated in critically revising the manuscript.

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