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Association of diet quality and physical activity with healthy ageing in the French NutriNet-Santé cohort

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Abstract

A growing number of studies have explored overall health during ageing in a holistic manner by investigating multidimensional models of healthy ageing (HA). However, little attention has been given to the role of adherence to national nutrition guidelines in that context. This study aimed to investigate the prospective association between adherence to the French nutrition guidelines and HA. The authors analysed data from 21 407 participants of the NutriNet-Santé study with a median baseline age of 55·6 years (2009–2014) and initially free of major chronic diseases. HA was defined as not developing major chronic disease, no depressive symptoms, no function-limiting pain, independence in instrumental activities of daily living, good physical, cognitive and social functioning, as well as good self-perceived health. Adherence to guidelines of the French Nutrition and Health Programme (Programme National Nutrition Santé or PNNS) was measured via the PNNS Guideline Score (PNNS-GS), using baseline data from repeated 24-h dietary records and physical activity questionnaires. After a median follow-up of 5·7 years, 46·3 % of participants met our HA criteria. Robust-error-variance Poisson regression revealed that higher PNNS-GS scores, reflecting higher adherence to nutrition recommendations (including both diet and physical activity guidelines), were associated with a higher probability to age healthily (relative risk$_{\text{quartile 4 } v. \text{ quartile 1}}$ = 1·17 (95 % CI 1·12, 1·22)). Supplementary analyses revealed that this association may, to a small part, be mediated by weight status. The results suggest that high adherence to the French national nutrition recommendations may be linked to better overall health throughout ageing.

Key words: **Epidemiology: Healthy ageing: Diet: Multidimensional concepts**

Age-related chronic diseases and functional decline in the elderly present an important public health and societal burden[1,2]. Both scientists and health policy makers have been highlighting the importance to not only focus on the occurrence of specific age-related diseases but to take a more holistic point of view that also considers physical, cognitive, social and mental functioning[3]. In that context, multidimensional concepts of 'healthy ageing (HA)' or 'successful ageing' are increasingly discussed and studied. A large part of such HA concepts are based on the definition proposed by Rowe & Kahn[4], including three components: the absence of disease and disability, good physical/cognitive functioning and an active engagement with life.

Among the different modifiable factors that can be targeted to help maintain good overall functioning and the avoidance of disease and disability throughout ageing, diet and physical activity are prominent[5–7]. Only few studies have investigated the relationship between adherence to national nutrition guidelines and multidimensional concepts of HA[8,9] – despite the need to better understand the effectiveness of such guidelines, widely disseminated in the general population, for preventing overall health decline in the elderly. Hence, the objective of our study was to investigate the association of adherence to the French national nutrition guidelines of the Programme National Nutrition Santé (PNNS), measured by the PNNS-Guidelines Score (PNNS-GS), with a multidimensional concept of HA. A secondary objective was to examine body weight status at baseline as a potentially mediating factor. As both dietary quality[9–11] and body weight status[12–14] have been associated with multidimensional HA, we hypothesised that adherence to dietary guidelines could affect overall health during ageing both by direct mechanisms and by protecting from overweight and obesity. We thus applied counterfactual-based mediation analysis to disentangle such direct and indirect relationships.

Abbreviations: HA, healthy ageing; PNNS, Programme National Nutrition Santé (French Nutrition and Health Programme); PNNS-GS, PNNS Guideline Score; RR, relative risk; SU.VI.MAX, Supplementation en Vitamines et Mineraux Antioxydants.

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Table 1. Description of the definition of multidimensional healthy ageing used for the NutriNet-Santé study

Criterion	Definition in the NutriNet-Santé cohort	Corresponding Rowe & Kahn criterion[4]
Good physical functioning	Evaluated using the 8 non-redundant items on limitations of (physical) activities included in the SF-36: no severe limitation ('limited a lot') on any item and less than five slight limitations ('limited a little')	Maintenance of high physical and cognitive function
Good cognitive functioning	Evaluated using the 7 items of the Cache County Study – metacognition questionnaire for the elderly: no severe decline ('much worse') concerning any item and less than three occurrences of slight decline ('a bit worse') among the 6 items explicitly related to cognitive functioning (i.e. excluding the item on household work, hobbies, and other interests)	Maintenance of high physical and cognitive function
No limitations in IADL	<1 limitation (among all items except the item on telephone usage, which appears no longer pertinent in the 2010s)	Avoiding disease and disability
No depressive symptoms	CES-D<16/60	–
No health-related limitations in social life	SF-36 responses: 1–2 to item 6 and 3–5 to item 10	Sustained engagement in social and productive activities
Good overall self-perceived health	SF-36 responses: 1–3 to item 1	–
No function-limiting pain	SF-36 responses: 1–3 to item 7 and/or 1–2 to item 8	–
No incident major chronic disease	– No self-reported CVD (heart disease, stroke events, peripheral artery disease), diabetes, cancer, pulmonary disease, renal disease or liver disease – No self-reported depression for which the participant is currently treated – No self-reported arthrosis, back pain and rheumatoid arthritis that are perceived as limiting for the participant and for which the participant is currently treated	Avoiding disease and disability

SF-36, Medical Outcome Study Short Form-36; IADL, Instrumental Activities of Daily Living; CES-D, Center for Epidemiologic Studies Depression Scale.

Methods

Study design

The French NutriNet-Santé study is an ongoing web-based cohort study for which inclusions started in May 2009. Detailed information on the study has been published previously[15]. Study participants were recruited among the French general population, while specifically focusing on Internet-using individuals aged ≥18 years. Information is collected via online questionnaires available on a dedicated web platform, at baseline and every year thereafter. The enquired information includes data on sociodemographic indicators, lifestyle characteristics including dietary intakes and physical activity and health data. All participants included into the NutriNet-Santé study provided informed consent. Moreover, the NutriNet-Santé study was approved by the international review board of the French Institute for Health and Medical Research (0000388FWA00005831) and the Comité National Informatique et Liberté (908450 and 909216). The study is registered at clinicaltrials.gov under the number NCT03335644.

Definition of 'healthy ageing'

Information on data related to HA was collected via a dedicated self-administered questionnaire that was proposed between 1 October 2015 and 31 March 2016.

Our definition of HA was largely based on the model proposed by Rowe & Kahn[4]. Thus, HA was defined as follows: (A) the absence of different chronic diseases (among others: cancer, cardiovascular disease, diabetes, renal disease and liver disease), limitations in instrumental activities of daily living, function-limiting pain, depressive symptomatology and health-related limitations in social life and (B) the presence of good physical and cognitive functioning and good overall self-perceived health. A comprehensive description of these different components is presented in Table 1. HA was defined as a dichotomous variable (meeting all listed criteria or not).

Baseline diet and physical activity data (2009–2014)

Dietary data were collected using repeated 24-h dietary records. Participants could complete one dietary assessment consisting of three dietary records every 6 months. These three records were randomly distributed across a 2-week period, while ensuring that two weekdays and one weekend day were covered. Completing a 24-h dietary record consisted in reporting all foods and beverages consumed at each eating occasion. Portion size estimation was facilitated by photographs derived from a validated picture booklet[16] including >250 generic foods corresponding to >2000 specific food items, presented in three main portion sizes. It was also possible to directly indicate consumed quantities or volumes.

For the present analysis, all dietary records provided during the first 2 years following inclusion were considered. On average, participants had provided 8·2 (SD 2·5) records (minimum 3; maximum 15 records). Alcohol consumption was estimated via a specific frequency questionnaire, and fish and seafood consumption was estimated based on a specific frequency question. Average daily food consumptions were estimated from the available dietary records, weighted for the type of day. Nutrient intakes were computed using the *ad hoc* NutriNet-Santé food composition table, which includes >3000 food items. Previous publications based on NutriNet-Santé data have validated the use of web-based 24-h dietary records in comparison with

interviews by trained dietitians[17] and against urine and plasma biomarkers[18,19].

Energy underreporting was detected based on the method developed by Black[20] and those identified as under-reporters were not included into the present analyses.

A short form of the French version of the International Physical Activity Questionnaire was used to assess leisure-time physical activity. Metabolic equivalent of task minutes per week was estimated and transformed into three different physical activity levels, according to the guidelines of the PNNS: low (<30 min/d), moderate (30–59 min/d) and high (≥60 min/d).

The computation of the PNNS-GS has been previously published in detail[21]. The score includes twelve diet-related components and one physical activity-related component that represent the guidelines of the French National Nutrition and Health Programme launched in 2001[22]. Scoring and cut-off values for each component are presented in Table 2. To obtain the final score, the points for each component are summed, and a penalty for energy overconsumption is applied if reported energy intakes exceed estimated energy needs by >5 %. In this case, the PNNS-GS is reduced by a fraction that is identical to the proportion by which energy needs are exceeded. The final score can theoretically be negative, and the possible maximum is fifteen points. We also calculated a modified PNNS-score (the mPNNS-GS), which only included the twelve diet-related components and no physical activity component.

Baseline anthropometric data

A validated web-based anthropometric questionnaire was used to collect self-reported information on height and weight at baseline[23,24]. BMI was calculated and categories were created as follows: underweight and normal weight (BMI < 25 kg/m^2), overweight (25 ≤ BMI < 30 kg/m^2) and obesity (BMI ≥ 30 kg/m^2).

Other baseline data

NutriNet-Santé participants are asked to complete web-based questionnaires on sociodemographic and lifestyle data at baseline and annually thereafter. These questionnaires provide information on sex, age, educational level, monthly income, socio-professional category, retirement status, living arrangement and smoking status. Socio-professional category either concerned the current occupation or the most recent occupation for unemployed or retired individuals. For income level, a 'category of missing values' was also created.

Study sample selection

We included participants who replied to the questionnaire on HA status (n 28 593), aged ≥45 years when completing this questionnaire (n 28 489), without cancer, cardiovascular disease or diabetes at study inclusion (n 24 915), with ≥3 valid dietary records during the first 2 years following inclusion (n 22 402), with available data to compute the PNNS-GS (n 21 772) and no missing data on covariables (n 21 407).

It should be noted that the questionnaire on HA was facultative (i.e. not one of the core questionnaires that NutriNet-Santé participants are regularly asked to complete). Hence, NutriNet participants who were eligible to complete this questionnaire (i.e. those aged ≥45 years) but did not respond may have done so for a variety of reasons: loss to follow-up (due to reasons unrelated to health such as decreased interest or due to health problems), no interest in completing this particular questionnaire or death.

Statistics

Sample size calculation. Our study can be considered as an exploratory analysis of a large-scale observational study. Hence, no calculations related to sample size or statistical power were done.

Descriptive statistics. Participant characteristics were compared according to HA status, using Mann–Whitney U- and χ^2 tests. Moreover, proportions of adherence to individual nutritional recommendations were compared according to HA status via χ^2 tests.

Main analyses. As the interpretation of OR as proxies for relative risks (RR) is only valid for rare outcomes (<10 %), we used an alternative multivariable model referred to as 'robust-error variance Poisson regression' to directly estimate RR[25] (i.e. instead of applying logistic regression).

The main exposure variables were the PNNS-GS and the mPNNS-GS, modelled as quartiles and as continuous variables, and the outcome of interest was HA status (yes/no).

A first model (model 1) was adjusted for age at follow-up and sex, and a second model (model 2) was additionally adjusted for overall energy intake, follow-up time, number of dietary records, educational level, socioprofessional category, income level, living alone (yes/no) and retirement status (yes/no). A third model (model 3, our main model) was also adjusted for smoking status. When modelling the mPNNS-GS as an exposure variable, this third model was also additionally adjusted for physical activity level. Family history of cardiovascular disease (yes/no) was also considered as a potentially confounding factor but not retained as a covariate within our final models as additional adjustment for this factor did not change our main results. Tests for linear trend consisted in modelling score quartiles as ordinal variables.

Tests for interaction. We tested effect modification by age and sex by inserting interaction terms into the fully adjusted models. There was no significant interaction between age and the PNNS-GS score or between sex and the PNNS-GS score (both P > 0·10).

Sensitivity analyses. A first sensitivity analysis consisted in excluding participants with a follow-up <5 years, to reinforce the prospective nature of the present analyses and hence reduce potential reverse causation bias. A second sensitivity analyses aimed to verify whether the investigated association was mainly driven by one or several specific components of the PNNS-GS. We thus created several modified versions of this diet quality score, in addition to the mPNNS-GS from which the physical activity component was removed: twelve additional modified PNNS-GS scores were created by removing each component

Table 2. Adherence to nutritional recommendations according to healthy ageing (HA) status (NutriNet-Santé Study, France, *n* 21 407)* (Numbers of participants and percentages)

	HA = 0 (*n* 11 486)		HA = 1 (*n* 9921)		
Adherence to the different PNNS-GS recommendations	*n*	%	*n*	%	*P*†
Recommendation concerning alcoholic beverages					<0·001
Ethanol >20 g/d (women)/>30 g/d (men): 0 points	1210	10·5	917	9·2	
Ethanol ≤20 g/d (women)/≤30 g/d (men): 0·8 points	8866	77·2	7958	80·2	
Alcohol consumed less than once a week: 1 point	1410	12·3	1046	10·5	
Recommendation concerning physical activity					<0·001
<30 min of brisk walking/d: 0 points	2612	22·7	1846	18·6	
30–59 min of brisk walking/d: 1 point	2647	23·0	2204	22·2	
≥60 min of brisk walking/d: 1·5 points	6227	54·2	5871	59·2	
Recommendation concerning non-alcoholic beverages					<0·001
<1 litre water and >250 ml soda/d: 0 points	57	0·5	36	0·4	
≥1 litre water and >250 ml soda/d: 0·5 points	56	0·5	49	0·5	
<1 litre water and ≤250 ml soda/d: 0·75 points	3817	33·2	3003	30·3	
≥1 litre water and ≤250 ml soda/d: 1 point	7556	65·8	6833	68·9	
Recommendation concerning whole grain foods					0·01
<33·3 % of consumed breads and grains: 0 points	7806	68·0	6553	66·1	
33·3 to 66·6 % of consumed breads and grains: 0·5 points	2969	25·8	2716	27·4	
≥ 66·7 % of consumed breads and grains: 1 point	711	6·2	652	6·6	
Recommendation concerning bread, cereals, potatoes and legumes					0·008
<1 portion/d: 0 points	266	2·3	205	2·1	
1–2 portions/d or >6 portions/d: 0·5 points	6519	56·8	5454	55·0	
3–6 portions/d: 1 point	4701	40·9	4262	43·0	
Recommendation concerning fruits and vegetables					<0·001
<3·5 portions/d: 0 points	1686	14·7	1259	12·7	
3·5–4·9 portions/d: 0·5 points	2631	22·9	2247	22·6	
5·0–7·4 portions/d: 1 point	4534	39·5	4025	40·6	
≥7·5 portions/d: 1·5 points	2635	22·9	2390	24·1	
Recommendation concerning sweetened foods					0·04
Added sugar from sweetened foods ≥17·5 % EI/d: –0·5 points	224	2·0	150	1·5	
Added sugar from sweetened foods 17·5–12·5 % EI/d: 0 points	1611	14·0	1370	13·8	
Added sugar from sweetened foods <12·5 % EI/d: 1 point	9651	84·0	8401	84·7	
Recommendation concerning added fat					0·34
Lipids from added fat >16 % EI/d: 0 points	2076	18·1	1742	17·6	
Lipids from added fat ≤16 % EI/d: 1 point	9410	81·9	8179	82·4	
Recommendation concerning vegetable added fat					0·71
No use of vegetable oil or ratio vegetable oil/total added fats ≤0·5: 0 points	2734	23·8	2339	23·6	
No use of added fats or ratio vegetable oil/total added fats >0·5: 1 point	8752	76·2	7582	76·4	
Recommendation concerning dairy products					0·42
<1 portion/d or 3·5 portions/d: 0 points	2529	22·0	2259	22·8	
1–2·4 portions/d: 0·5 points	5180	45·1	4432	44·7	
2·5–3·4 portions/d: 1 point	3777	32·9	3230	32·6	
Recommendation concerning sea food					0·96
< 2/week: 0 points	4710	41·0	4064	41·0	
≥ 2/week: 1 point	6776	59·0	5857	59·0	
Recommendation concerning salt					0·046
>12 g/d: –0·5 points	1418	12·3	1191	12·0	
10–11 g/d: 0 points	1979	17·2	1661	16·7	
8–9 g/d: 0·5 points	3273	28·5	2910	29·3	
6–7 g/d: 1 point	3337	29·1	2989	30·1	
≤6 g/d: 1·5 points	1479	12·9	1170	11·8	
Recommendation concerning meat, poultry, sea food and eggs					0·08
0 portions/d: 0 points	28	0·2	39	0·4	
0·1–0·9 portions/d or > 2 portions/d: 0·5 points	4255	37·0	3746	37·8	
1–2 portions/d: 1 point	7203	62·7	6136	61·8	

PNNS-GS, Programme National Nutrition-Santé (French National Nutrition and Health Programme) Guidance Score; EI, overall energy intake; PNNS, Programme National Nutrition-Santé.

* This table shows the attribution of points underlying the construction of the PNNS-GS, as well as percentages of adherence to the different recommendations of the PNNS.

† Unadjusted χ^2 tests.

one by one. The respective models were additionally adjusted for the removed component.

Mediation analyses. A supplementary analysis was conducted to characterise the mediating role of BMI status (normal weight/overweight/obese) in the association between the PNNS-GS and HA. The methodology of this mediation analysis was based on the counterfactual-based approach proposed by Lange *et al.*[26] This methodological approach included the following steps: (1) PNNS-GS quartiles were considered as the exposure (A), BMI class as the mediator (M) and HA as the outcome (Y). (2) A new data set was created that included a new variable A*, corresponding to each of the four PNNS-GS quartiles. For each participant, this new data set included four lines:

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one line in which A* corresponds to the reality, and three lines in which the participant was part of another PNNS-GS quartile than in reality. (3) Two logistic regression models (adjusted for potential confounders) were run on the above-described new data set, to model the relationship between BMI class and PNNS-GS quartiles: in the first logistic regression model, the original variable 'A' was used for this purpose, and in the second model, the new variable 'A*' was used. (4) Based on these two logistic regression models, predicted probabilities were extracted and transformed to 'weights' as follows: $W_i^C = P(M = M_i|A = A_i^*, C = C_i)/P(M = M_i|A = A_i, C = C_i)$ with *i:* the individual; *A:* the observed exposure; *A*:* the created exposure; *M:* the mediator; *C:* potential confounding factors (i.e. the same covariables as those used in our main analysis). (5) We ran a weighted and confounder-adjusted robust-error Poisson regression model to obtain relative risk estimates for the relationship of both A and A* with HA. The relative risk associated with A was interpreted as the direct association between PNNS-GS quartiles and HA, and the RR associated with A* was interpreted as the indirect relation mediated by BMI class.

All analyses were performed using 9.4 version of the SAS software (SAS Institute Inc.). All *P*-values were two sided, and *P*-values <0·05 were considered as statistically significant.

Results

Our study sample's mean age at follow-up was 60·6 (SD 8·5) years and the mean follow-up time was 5·2 (SD 1·4, median = 5·7, first quartile = 4·4, third quartile = 6·4) years. The criteria of HA were met by 47·5 % of men and 45·9 % of women.

Descriptive statistics

Table 2 presents adherence to the individual recommendations of the French Nutrition and Health Programme (PNNS) at baseline, according to HA status. Those characterised as 'healthy agers' at follow-up showed more favourable baseline behaviours concerning physical activity and the consumption of several food groups. Table 3 presents general baseline characteristics of participants according to HA status. 'Healthy agers' were slightly younger, more often men, had a higher educational level and income level. They were more often in more 'advantaged' socioprofessional categories, were less often retired, less often living alone and less often smokers. Table 4 presents the distribution of individuals that met/did not meet the different criteria of our HA definition. The factors that were the most related to not meeting our definition were the presence of chronic diseases and of depressive symptoms, as well as self-reported decline in cognitive function.

Main analyses

Table 5 presents the association of PNNS-GS and mPNNS-GS quartiles with HA. In the fully adjusted model, both PNNS-GS and mPNNS-GS quartiles were positively related to multidimensional HA status. The RR associated with being in the fourth *v.* in the first quartile of the PNNS-GS was 1·17 (95 % CI 1·12, 1·22). The RR associated with being in the fourth *v.* in the first mPNNS-GS quartile was lower (1·08 (95 % CI 1·14, 1·13)).

Table 3. Participant characteristics at baseline according to healthy ageing (HA) status (NutriNet-Santé Study, France, *n* 21 407)
(Numbers of participants and percentages; medians and 25th and 75th percentiles)

	HA = 0		HA = 1		
	n	%	*n*	%	*P**
Follow-up time (months)					0·3
Median	68·5		68·3		
25th and 75th percentiles	52·7, 76·3		52·6, 76·3		
Age (years) at follow-up					<0·001
Median	61·7		59·6		
25th and 75th percentiles	54·3, 67·8		52·9, 66·1		
Age class at follow-up					<0·001
45–54 years	3106	27·0	3209	32·3	
55–64 years	4008	34·9	3764	37·9	
65–74 years	3682	32·1	2701	27·2	
≥75 years	690	6·0	247	2·5	
BMI (kg/m^2)					<0·001
Median	23·8		23.0		
25th and 75th percentiles	21·6, 26·8		21·1, 25·4		
BMI category					<0·001
Normal weight/underweight	7097	61·8	7156	72·1	
Overweight	3104	27·0	2243	22·6	
Obesity	1285	11·2	522	5·3	
Women	8426	73·4	7148	72·0	0·033
Educational level					<0·001
Pre-high school level only	3152	27·4	2235	22·5	
High school level	1817	15·8	1541	15·5	
University degree	6517	56·7	6145	61·9	
Monthly income per consumption unit					<0·001
Not available	1146	10·0	865	8·7	
<1200 €	1253	10·9	886	8·9	
1200 €–1799 €	2617	22·8	2115	21·3	
1800 €–2699 €	2871	25·0	2474	24·9	
≥2700 €–3699 €	3599	31·3	3581	36·1	
Socioprofessional category					<0·001
Employee	3116	27·1	2281	23·0	
Intermediate profession	3553	30·9	3180	32·1	
Self-employed	433	3·8	381	3·8	
Managerial staff or intellectual profession	4334	37·7	4031	40·6	
Never employed	50	0·4	48	0·5	
Retired	4435	38·6	3194	32·2	<0·001
Living alone	2806	24·4	2150	21·7	<0·001
Smoking status					<0·001
Non-smoker	5054	44·0	4143	41·8	
Former smoker	5172	45·0	4823	48·6	
Smoker	1260	11·0	955	9·6	
PNNS-GS (/15 points)					<0·001
Median	9·5		9·8		
25th and 75th percentiles	8·3, 10·8		8·3, 10·8		
Modified PNNS-GS (/13·5 points)					<0·001
Median	8·3		8·6		
25th and 75th percentiles	7·3, 9·5		7·3, 9·6		
Energy intake (kcal/d)†					0·079
Median	1834		1843		
25th and 75th percentiles	1564, 2169		1587, 2162		

PNNS-GS, Programme National Nutrition-Santé (French National Nutrition and Health Programme) Guidance Score.
* Mann–Whitney *U* tests for continuous variables and χ^2 tests for categorical variables.
† To convert energy in kcal/d to kJ/d, multiply by 4·184.

Results concerning the PNNS-GS and mPNNS-GS modelled as standardised continuous scores are shown as part of Table 6.

Sensitivity analyses

Our sensitivity analyses in which we only included participants with a follow-up time ≥5 years (*n* 13 668, see Table 7) showed

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Table 4. Proportion of participants corresponding to specific criteria of the NutriNet-Santé definition of multidimensional healthy ageing (HA) (NutriNet-Santé Study, France, *n* 21 407)

Criterion of Rowe & Kahn's concept[4]	Criterion of the NutriNet-Santé definition	% corresponding to criterion	% not corresponding to criterion	% not corresponding among those with HA = 0	% of those with HA = 0 corresponding to all criteria except this one
Avoidance of disease and disability	No major chronic disease or limitations in instrumental activities of daily living	70	30	55·9	22·3
	Absence of disease (i.e. no incident diabetes, cancer, or CVD)	74·8	25·2	46·9	16·4
	No limitations in Instrumental Activities of Daily Living	92	8	14·9	4·8
Maintenance of high physical and cognitive function	Good physical functioning	86·5	13·5	25·1	3·1
	Good cognitive functioning	82·6	17·4	32·4	12·7
Sustained engagement in social and productive activities	No health-related limitations in social life	87·3	12·7	23·7	2·5
None	Other criteria				
	Good mental health (no depressive symptoms)	82·3	17·7	32·9	7·6
	No function-limiting pain	87·9	12·1	22·6	2·1
	Good perceived health	94·5	5·5	10·2	0·3

Table 5. Relationship between quartiles (Q) of the Programme National Nutrition-Santé Guideline Score (PNNS-GS) and modified PNNS-GS (mPNNS-GS; i.e. without the physical activity component) and the probability of overall healthy ageing (NutriNet-Santé Study, France, *n* 21 407)* (Relative risks (RR) and 95 % confidence intervals)

		$RR_{Q2\ v.\ Q1}$		$RR_{Q3\ v.\ Q1}$		$RR_{Q4\ v.\ Q1}$		P_{trend}
Tested diet score	Model†	RR	95 % CI	RR	95 % CI	RR	95 % CI	
PNNS-GS	Model 1	1·08	1·03, 1·12	1·15	1·11, 1·20	1·20	1·15, 1·25	<0·001
PNNS-GS	Model 2	1·07	1·02, 1·12	1·14	1·09, 1·19	1·18	1·13, 1·23	<0·001
PNNS-GS	Model 3	1·06	1·02, 1·11	1·13	1·09, 1·18	1·17	1·12, 1·22	<0·001
mPNNS-GS	Model 1	1·05	1·01, 1·10	1·10	1·06, 1·15	1·13	1·09, 1·18	<0·001
mPNNS-GS	Model 2	1·04	1·00, 1·09	1·09	1·04, 1·13	1·11	1·07, 1·16	<0·001
mPNNS-GS	Model 3	1·03	0·99, 1·07	1·07	1·02, 1·11	1·08	1·04, 1·13	<0·001

P_{trend}, *P* value for linear trend across quartiles.
* RR were estimated using robust-error Poisson regression. RR higher than 1 indicate an increased probability of multidimensional healthy ageing. Range of PNNS-GS score within each quartile: 0·1–8·3 (Q1), 8·3–9·5 (Q2), 9·6–10·8 (Q3), 10·8–14·5 (Q4). Range of mPNNS-GS score within each quartile: 0·1–7·3 (Q1), 7·3–8·5 (Q2), 8·5–9·5 (Q3), 9·6–13·0 (Q4).
† Model 1: adjusted for age at follow-up and for sex; model 2: additionally adjusted for overall energy intake, follow-up time, number of dietary records, educational level, socioprofessional category, income level, living arrangement (i.e. living alone: yes/no) and retirement status (yes/no); model 3: additionally adjusted for smoking status and physical activity level (except for the PNNS-GS which was not adjusted for physical activity level).

even stronger associations of the PNNS-GS and of the mPNNS-GS with HA than our main analyses. Moreover, our analyses showing the relationship between different types of modified versions of the PNNS-GS and HA (Table 6) indicated that apart from the physical activity component, no other component had a dominant role in the investigated association.

Mediation analyses

Our supplementary mediation analyses revealed a significant but small 'natural indirect effect' related to BMI status, indicating that the relationship between adherence to the French nutrition guidelines and overall HA may, to a small extent, be mediated by BMI status (Table 8). The estimated proportion of the association mediated by BMI status was 12·4 %, for a comparison of the fourth *v.* the first PNNS-GS quartile.

Discussion

Summary of findings

In this large cohort of French adults, a higher adherence to the French Nutrition and Health Programme food-based dietary guidelines was related to a higher probability of later HA. This relationship was particularly pronounced when considering the combined role of an elevated physical activity level and high dietary quality. Of note, the observed association was even slightly stronger when only including participants with a

Table 6. Association between modified versions of the Programme National Nutrition-Santé Guideline Score (PNNS-GS) and multidimensional healthy ageing status (NutriNet-Santé Study, France, *n* 21 407)*
(Relative risks (RR) and 95 % confidence intervals)

Tested diet score	RR	95 % CI	$P_{continuous}$
PNNS-GS	1·07	1·05, 1·09	<0·001
PNNS-GS without physical activity component (=modified PNNS-GS)	1·04	1·02, 1·05	<0·001
PNNS-GS without fruits and vegetables component	1·06	1·04, 1·08	<0·001
PNNS-GS without bread, cereals, potatoes and legumes	1·07	1·05, 1·09	<0·001
PNNS-GS without whole grain food component	1·07	1·05, 1·08	<0·001
PNNS-GS without milk and dairy products component	1·07	1·05, 1·09	<0·001
PNNS-GS without meat and poultry, seafood and eggs component	1·07	1·06, 1·09	<0·001
PNNS-GS without seafood component	1·07	1·06, 1·09	<0·001
PNNS-GS without sweetened foods component	1·07	1·05, 1·08	<0·001
PNNS-GS without total added fats component	1·08	1·06, 1·09	<0·001
PNNS-GS without vegetable added fats component	1·07	1·06, 1·09	<0·001
PNNS-GS without alcohol component	1·07	1·06, 1·09	<0·001
PNNS-GS without beverages component	1·07	1·05, 1·08	<0·001
PNNS-GS without salt component	1·07	1·05, 1·08	<0·001

* This table presents the relationship between the PNNS-GS and modified versions of this score, modelled as standardised (i.e. Z-score transformed) continuous variables, with multidimensional healthy ageing. RR were estimated using robust-error Poisson regression. Analyses were adjusted for age, sex, overall energy intake, follow-up time, number of dietary records, educational level, socioprofessional category, income level, living arrangement (i.e. living alone: yes/no) and retirement status (yes/no), and smoking status. Moreover, for each modified version of the PNNS-GS, there was an additional adjustment for the component removed from the initial PNNS-GS score.

follow-up of ≥5 years, thus strengthening the prospective nature of our analyses.

Supplementary analyses using modified PNNS-GS scores indicated that the different diet-related components appeared to contribute similarly to the overall relationship. Hence, the combined role of meeting all or several different recommendations seems to be important for maintaining a good overall health status during ageing. The supplemental analyses performed to investigate a potential indirect effect related to BMI status indicated a significant but small mediation of the investigated relationship by corpulence. A very similar observation was made in a previous study based on data from the Supplementation en Vitamines et Mineraux Antioxydants (SU.VI.MAX) study in which 5 % of the prospective association between adherence to the French national nutrition guidelines and multidimensional HA was estimated to be mediated by BMI status[27].

Comparison with the literature

To our knowledge, only the French and the Australian national nutrition guidelines have been investigated in relation to multidimensional concepts of HA. An analysis of data from 2329 participants of the French SU.VI.MAX study has shown that a higher adherence to the French nutrition guidelines (as measured by the PNNS-GS) at midlife was related to a higher probability of HA 13 years later[9]. HA was defined in a similar manner as in the present study but combined self-reported information and objective clinical data (while in the present study, all information was self-reported). In that study based on data from the SU.VI.MAX cohort, the strength of the association was higher ($OR_{4\ v.\ quartile\ 1\ of\ the\ PNNS\text{-}GS} = 1{\cdot}61$ compared with an OR of 1·35 in the present study when calculating OR rather than RR, data not shown). It can be hypothesised that this may be related to the longer follow-up time of the study based on SU.VI.MAX data and to the fact that the HA definition used in the SU.VI.MAX study also used objective clinical information.

A study based on data from 1609 participants of the Australian Blue Mountains Eye Study has found a positive association between adherence to the Australian dietary guidelines and a multidimensional concept of 'successful ageing', after a follow-up of 10 years. In that study, 'successful ageing' was defined as the absence of major chronic diseases, independence in instrumental activities of daily living as well as functional independence, good cognitive, mental and respiratory functioning, as well as blood pressure within a healthy range.

Five other studies have focused on dietary indicators that do not directly reflect adherence to official national nutrition recommendations, but high overall dietary quality[10,11], high adherence to the Mediterranean diet[11,28] or *a posteriori* dietary patterns[10,29,30].

A prospective investigation of data from the Nurses' Health Study found a positive relationship between higher scores on the Alternative Healthy Eating Index-2010 and a multidimensional concept of HA. On the other hand, the initial version of the Alternative Healthy Eating Index was not significantly associated with 'ideal ageing' in a study based on longitudinal data from the Whitehall II cohort. The aforementioned investigation of data from the SU.VI.MAX study has also focused on the Dietary Quality Index-International and the PANDiet index[9]. Although the Dietary Quality Index-International (a food- and nutrient-based index measuring overall dietary quality) was not related to HA, the PANDiet (measuring adequacy to nutrient-based dietary recommendations) showed a significant positive relationship with HA.

The association between adherence to the Mediterranean diet and HA was investigated within the French SU.VI.MAX study[28] and within the Nurses' Health Study[11]. In the SU.VI.MAX study, adherence to the Mediterranean diet at midlife – as measured by the Literature-based Adherence Score to the Mediterranean Diet and the relative Mediterranean Diet Score – showed a significant positive relationship with later HA. Likewise, in the Nurses' Health study, higher scores on the

Table 7. Sensitivity analysis: exclusion of participants with a follow-up time <5 years (leaving *n* 13 668 included in this analysis)* (Relative risks (RR) and 95 % confidence intervals)

Tested diet score	Model†	$RR_{Q2\ v.\ Q1}$		$RR_{Q3\ v.\ Q1}$		$RR_{Q4\ v.\ Q1}$		P_{trend}
		RR	95 % CI	RR	95 % CI	RR	95 % CI	
PNNS-GS	Model 1	1·11	1·05, 1·17	1·23	1·17, 1·29	1·23	1·16, 1·30	<0·001
PNNS-GS	Model 2	1·10	1·05, 1·17	1·21	1·15, 1·27	1·21	1·14, 1·28	<0·001
PNNS-GS	Model 3	1·10	1·04, 1·16	1·20	1·14, 1·26	1·19	1·13, 1·26	<0·001
mPNNS-GS	Model 1	1·09	1·03, 1·15	1·17	1·11, 1·23	1·17	1·11, 1·24	<0·001
mPNNS-GS	Model 2	1·08	1·02, 1·14	1·15	1·09, 1·21	1·15	1·09, 1·21	<0·001
mPNNS-GS	Model 3	1·06	1·01, 1·12	1·12	1·06, 1·18	1·11	1·06, 1·18	<0·001

Q, quartile; P_{trend}, *P* value for linear trend across quartiles; PNNS-GS, Programme National Nutrition-Santé Guideline Score; mPNNS-GS, modified Programme National Nutrition-Santé Guideline Score (i.e. without the physical activity component).
* This table presents the relationship between quartiles of the PNNS-GS and mPNNS-GS and the probability of overall healthy ageing, while excluding participants with a follow-up time <5 years. RR were estimated using robust-error Poisson regression. RR higher than 1 indicate an increased probability of multidimensional healthy ageing.
† Model 1: adjusted for age at follow-up and for sex; model 2: additionally adjusted for overall energy intake, follow-up time, number of dietary records, educational level, socioprofessional category, income level, living arrangement (i.e. living alone: yes/no) and retirement status (yes/no); model 3: additionally adjusted for smoking status and physical activity level (except for the PNNS-GS which was not adjusted for physical activity level).

Table 8. Mediation of the association between the Programme National Nutrition-Santé Guideline Score (PNNS-GS) and healthy ageing status by BMI status (normal weight, overweight, obese)*† (Relative risks (RR) and 95 % confidence intervals)

	$RR_{Q2\ v.\ Q1}$		$RR_{Q3\ v.\ Q1}$		$RR_{Q4\ v.\ Q1}$		P_{trend}
	RR	95 % CI	RR	95 % CI	RR	95 % CI	
Direct effect	1·06	1·02, 1·11	1·12	1·08, 1·17	1·15	1·10, 1·20	<0·001
Indirect effect	1·00	1·00, 1·00	1·01	1·01, 1·01	1·02	1·02, 1·02	<0·001
Mediation‡ (%)	4·9		8·4		12·4		

Q, quartile; P_{trend}, *P* value for linear trend across quartiles; NDE, natural direct effect; NIE, natural indirect effect.
* Mediation analysis was conducted using the methodology published by Lange *et al.*[26]. The direct effect corresponds to the direct relation between PNNS-GS quartiles and healthy ageing, and the indirect effect corresponds to the relation mediated by BMI status (<25, 25–29, ≥30 kg/m^2). Data come from the NutriNet-Santé Study, France (*n* 21 407).
† RR were estimated using robust-error Poisson regression adjusted for age, sex, overall energy intake, follow-up time, number of dietary records, educational level, socioprofessional category, income level, living arrangement (i.e. living alone: yes/no), retirement status (yes/no), and smoking status.
‡ Values correspond to the percentage of the total association mediated by BMI status. The proportion mediated was computed as $(RR_{NDE}(RR_{NIE} - 1)) \div (RR_{NDE} \times RR_{NIE} - 1) \times 100$ %.

Alternate Mediterranean Diet Score were prospectively related to a higher probability of HA.

Measures of the overall diet that involve empirically derived dietary patterns are quite different from measures based on *a priori* constructed dietary scores. Yet, results from three studies that have used principal component analysis to extract such *a posteriori* dietary patterns[10,29,30] are also in line with the results of the present study. In summary, these three studies emphasise a beneficial role of dietary patterns high in fruits, vegetables, vegetable fat, whole grains and fish and a detrimental role of dietary patterns high in meat and fatty foods.

As expected, our study shows a potentially important role of physical activity for HA, as removal of the physical activity component from the PNNS-GS lead to a substantial decrease in the strength of the association with HA. This is in line with the findings of a recent meta-analysis of prospective observational studies on the relationship between physical activity and (mostly multidimensional) HA concepts[7].

Limitations and strengths

Our investigation has several limitations. First, no measure of HA status was available at baseline. However, participants were free of major chronic disease, thus strengthening our working hypothesis that individuals were initially healthy. Second, our study sample was not representative of the French general population, as the NutriNet-Santé study included volunteers and has been shown to include more females and individuals with higher education compared with the general population[31]. Third, the different components of our multidimensional HA construct relied on self-reported data. Fourth, the time of follow-up (median = 5·7) was relatively short. Moreover, given the facultative nature of the NutriNet-Santé HA questionnaire, it was difficult to disentangle non-responses to the questionnaire due to health-unrelated reasons (such as lack of interest in this particular questionnaire or in continued study participation in general) from health-related reasons (i.e. functional limitations preventing participants from continued study participation and death). Non-responses related to health decline and death may have led to an underestimation of the investigated relationship (under the hypothesis that poor diet was implicated in health decline among such participants). The fact that deceased participants were not included into our study is also of importance in the light of the observed 'gender paradox', which implies that men tend to die earlier than women despite less co-morbidities and disabilities[32]. The lower proportion of HA among women compared with men that was observed in

our study is likely a reflection of this paradox because our study's HA definition did not include the notion of 'avoiding premature death'.

A major strength of our study is the availability of a very large data set of >20 000 individuals. Moreover, dietary data were estimated in a particularly precise manner, using a validated methodology of repeated 24-h dietary records – with, on average, eight available records per participant. In addition, mediation analysis emphasised the direct association of high dietary quality and physical activity with HA.

Conclusion

These results indicate that higher adherence to the French nutrition recommendations may be linked to a higher probability of maintaining good overall health during ageing – including disease-related dimensions, functional dimensions, as well as perceived health. Further research is needed to define public health strategies that efficiently help individuals to make changes in their day-to-day lives, towards an improved dietary quality and increased engagement in physical activities.

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