

Clustering of adherence to personalised dietary recommendations and changes in healthy eating index within the Food4Me study

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Title**Clustering of adherence to personalised dietary recommendations and changes in healthy eating index within the Food4Me Study****Author names**

Katherine M. Livingstone*¹, Carlos Celis-Morales*¹, Jose Lara¹, Clara Woolhead², Clare B. O'Donovan², Hannah Forster², Cyril F.M. Marsaux³, Anna L. Macready⁴, Rosalind Fallaize⁴, Santiago Navas-Carretero⁵, Rodrigo San-Cristobal⁵, Silvia Kolossa⁶, Lydia Tsirigoti⁷, Christina P. Lambrinou⁷, George Moschonis⁷, Agnieszka Surwiłło⁸, Christian A. Drevon⁹, Yannis Manios⁷, Iwona Traczyk⁸, Eileen R. Gibney², Lorraine Brennan², Marianne C. Walsh², Julie A. Lovegrove⁴, J. Alfredo Martinez⁵, Wim H. Saris³, Hannelore Daniel⁶, Mike Gibney², John C. Mathers¹, on behalf of the Food4Me Study.

Author affiliations

1, Human Nutrition Research Centre, Institute of Cellular Medicine, Newcastle University, Newcastle Upon Tyne, UK (KML, katherine.livingstone@newcastle.ac.uk, JL, jose.lara@newcastle.ac.uk, CCM, carlos.celis@newcastle.ac.uk; JCM, john.mathers@newcastle.ac.uk)

2, UCD Institute of Food and Health, University College Dublin, Belfield, Dublin 4, Republic of Ireland (CBD, clare.odonovan@ucdconnect.ie; HF, hannah.forster@ucdconnect.ie; CW, clara.woolhead@ucdconnect.ie; EG, eileen.gibney@ucd.ie; LB, lorraine.brennan@ucd.ie; MCW, marianne.walsh@ucd.ie; MG, mike.gibney@ucd.ie)

3, Department of Human Biology, NUTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre, Maastricht, The Netherlands (CFMM, c.marsaux@maastrichtuniversity.nl; WHMS, w.saris@maastrichtuniversity.nl)

4, Hugh Sinclair Unit of Human Nutrition and Institute for Cardiovascular and Metabolic Research, University of Reading, Reading, UK (ALM, a.l.macready@reading.ac.uk; RF, r.fallaize@reading.ac.uk; JAL, j.a.lovegrove@reading.ac.uk)

5, Center for Nutrition Research, University of Navarra, Pamplona, Spain; CIBER Fisiopatología Obesidad y Nutrición (CIBERObn), Instituto de Salud Carlos III, Madrid, Spain (SNC, snavas@unav.es; RSC, rsan.1@alumni.unav.es; JAM, jalfmtz@unav.es)

6, ZIEL Research Center of Nutrition and Food Sciences, Biochemistry Unit, Technical University of Munich, Germany (SK, silvia.kolossa@tum.de; HD, hannelore.daniel@tum.de)

7, Department of Nutrition and Dietetics, Harokopio University, Athens, Greece (LT, tsirigoti.lydia@gmail.com; CPL, cplambrinos@gmail.com; GM, gmoschi@hua.gr; YM, manios@hua.gr)

8, National Food & Nutrition Institute (IZZ), Poland (AS, asurwillo@izz.waw.pl; IT, itraczyk@izz.waw.pl)

9, Department of Nutrition, Institute of Basic Medical Sciences, Faculty of Medicine, University of Oslo, Oslo, Norway (CAD, c.a.drevon@medisin.uio.no)

*KML and CCM are joint first-authors

Corresponding author; request for reprints

Professor John C. Mathers

Human Nutrition Research Centre

Institute of Cellular Medicine

Newcastle University

Biomedical Research Building

Campus for Ageing and Vitality

Newcastle upon Tyne

NE4 5PL, UK

john.mathers@newcastle.ac.uk

Tel: +44 (0) 1912081133 Fax: +44 (0) 1912081101

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Abbreviations: Body mass index (BMI); Cardiovascular disease (CVD); Food frequency questionnaire (FFQ); Healthy eating index (HEI); Physical activity level (PAL); Personalised Nutrition (PN); Randomized controlled trial (RCT); Sedentary behaviour (SB); Waist circumference (WC)

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Ethical standards disclosure: This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects/patients were approved by the Research Ethics Committees at each University or Research Centre delivering the intervention. The Food4Me trial was registered as a RCT (NCT01530139) at Clinicaltrials.gov. All participants expressing an interest in the study were asked to sign online consent forms at two stages in the screening process. These consent forms were automatically directed to the local study investigators to be counter-signed and archived.

1 **Abstract (words count=250)**

2 **Objective**

3 To characterize clusters of individuals based on adherence to dietary recommendations and to
4 determine whether changes in Healthy Eating Index (HEI) scores in response to a
5 personalised nutrition (PN) intervention varied between clusters.

6 **Design**

7 Food4Me study participants were clustered according to whether their baseline dietary
8 intakes met European dietary recommendations. Changes in HEI scores between baseline and
9 month 6 were compared between clusters and stratified by whether individuals received
10 generalized or PN advice.

11 **Setting**

12 Pan-European, internet-based, 6-month randomized controlled trial.

13 **Subjects**

14 Adults aged 18-79 years (*n* 1480).

15 **Results**

16 Individuals in cluster 1 (C1) met all recommended intakes except for red meat, those in
17 cluster 2 (C2) met two recommendations and those in cluster 3 (C3) and cluster 4 (C4) met
18 one recommendation each. C1 had higher intakes of white fish, beans and lentils and low fat
19 dairy products and lower percentage energy intakes from saturated fatty acids ($P<0.05$). C2
20 consumed less chips and pizza and fried foods than C3 and C4 ($P<0.05$). C1 were lighter, had
21 lower BMI and WC than C3 and were more physical active than C4 ($P<0.05$). More
22 individuals in C4 were smokers and wanted to lose weight than C1 ($P<0.05$). Individuals who
23 received PN advice in C4 reported greater improvements in HEI compared with C3 and C1
24 ($P<0.05$).

25 **Conclusions**

26 The cluster where the fewest recommendations were met (C4), reported greater
27 improvements in HEI following a 6-month trial of PN whereas there was no difference
28 between clusters for those randomised to the Control, non-personalised dietary intervention.

- 29 **Trial registration** – [Clinicaltrials.gov NCT01530139](https://clinicaltrials.gov/ct2/show/study/NCT01530139)
- 30 **Key Words** – Clustering; personalised nutrition; dietary recommendations; healthy eating
- 31 index

32 INTRODUCTION

33 Global obesity prevalence has reached epidemic proportions with 37% of men and 38% of
34 women now either overweight or obese ⁽¹⁾. Poor dietary choices and inadequate physical
35 activity are the primary causes of obesity ⁽²⁾. Current strategies for improving diet and other
36 lifestyle behaviours, such as consuming 5 portions of fruit and vegetables per day ⁽³⁾, are
37 based on “one size fits all” generalised dietary guidelines. Given that the burden of obesity is
38 increasing ⁽¹⁾, alternative strategies for improving dietary behaviours are being developed,
39 including predictive, personalised, preventative and participatory interventions ⁽⁴⁾. Recent
40 evidence suggests that genetic-based personalised nutrition (PN) improves dietary intakes
41 more than non-personalised advice ⁽⁵⁾. However, since dietary intakes tend to cluster ^(6; 7), it
42 may be possible to enhance the efficacy of interventions by further characterization of
43 participants according to their dietary and lifestyle behaviours and, subsequently, use this
44 information to strengthen the basis for personalization of the intervention. For example, lower
45 intakes of fruit, vegetables and wholegrains are often associated with higher intakes of red or
46 processed meat ⁽⁸⁾. In addition, less healthy dietary clusters are associated with increased
47 disease risk ⁽⁹⁾, and unhealthy dietary and lifestyle behaviours is associated with higher levels
48 of sedentary behaviour ⁽⁷⁾ and mortality ^(10; 11). Clustering individuals based on whether they
49 meet dietary recommendations may be a useful predictive tool for estimating response to an
50 intervention ^(12; 13; 14) and may help to stratify or personalise interventions.

51 The Food4Me proof-of-principle (PoP) study was the first internet-based study to
52 demonstrate that PN advice was more effective in improving dietary intakes, including
53 lowering intakes of red meat when compared with conventional “one size fits all” population-
54 based advice. However, the characteristics of individuals clustered on the basis of adherence
55 to current recommended dietary intake of fruit and vegetables, wholegrains, oily fish, dairy
56 products and red and processed meat, are unknown. Thus, the aims of this analysis were to i)
57 characterise European adults participating in the Food4Me study ⁽¹⁵⁾ according to clustering
58 based on European recommendations for healthy eating and ii) determine whether cluster
59 membership predicted dietary changes following a PN intervention.

60

61 METHODS

62 Study design and population

63 The Food4Me study was a 6-month, 4-arm, internet-based, RCT in 1607 individuals
64 conducted across 7 European countries ⁽¹⁵⁾. Participants were recruited via the Food4Me
65 website ⁽¹⁶⁾ to emulate a web-based PN service. This was aided by local and national
66 advertising of the study via the Internet, radio, newspapers, posters, e-flyers, social media and
67 word of mouth. Recruitment took place between August 2012 and August 2013 in the
68 following sites: University College Dublin (Ireland), Maastricht University (The
69 Netherlands), University of Navarra (Spain), Harokopio University (Greece), University of
70 Reading (United Kingdom, UK), National Food and Nutrition Institute (Poland), Technical
71 University of Munich (Germany). The Research Ethics Committees at each University or
72 Research Centre delivering the intervention granted ethical approval for the study. The
73 Food4Me trial was registered as a RCT (NCT01530139) at Clinicaltrials.gov. All participants
74 expressing an interest in the study were asked to sign online consent forms at two stages in
75 the screening process.

76

77 **Intervention arms**

78 Participants were randomized to receive non-personalised, generalised dietary advice
79 (Control), or one of three levels of PN (Level 1, Level 2 or Level 3). Briefly, non-
80 personalised dietary advice was based on national dietary recommendations in each of the 7
81 European countries. These “standardised” recommendations included advice on energy intake
82 and on the consumption of fruits and vegetables, wholegrains, fish, dairy products, meat, type
83 of fat and salt. Participants randomised to Level 1 received personalised dietary advice on
84 how their intakes of these food groups compared with guideline amounts. Participants
85 randomised to Level 2 received advice based on their dietary intake (as for Level 1) and also
86 on their baseline phenotypic data. The phenotypic feedback was based on anthropometric
87 measurements and nutrient- and metabolic-related biomarkers. Participants randomised to
88 Level 3 received advice based on their dietary intake, phenotypic and genotypic data
89 collected at baseline. The genotypic feedback was based on specific variants in five nutrient-
90 responsive genes selected specifically for the study. Further details are provided elsewhere
91 ⁽¹⁵⁾.

92

93 **Screening questionnaires and dietary intakes**

94 Participants eligible for inclusion in the RCT completed an online questionnaire to collect
95 detailed information on socio-demographic, health and anthropometric characteristics and
96 dietary habits. Following completion of this questionnaire, participants were asked to
97 complete an online food frequency questionnaire (FFQ) to estimate usual dietary intake. This
98 FFQ, which was developed and validated for this study^(17; 18), included 157 food items
99 consumed frequently in each of the 7 recruitment countries. Intakes of foods and nutrients
100 were computed in real time using a food composition database based on McCance &
101 Widdowson's "The composition of foods"⁽¹⁹⁾. Intakes of nutrients were assessed based on
102 standardised recommendations (**Supplementary Table 1**) for dietary intakes of foods and
103 food groups⁽²⁰⁾, which were integrated and harmonised across 8 European countries (UK,
104 Ireland, Germany, The Netherlands, Spain, Greece, Poland and Norway)^(21; 22; 23; 24). The
105 following 4 food group recommendations were used in the present analysis: eat at least 5
106 portions of fruit and vegetables every day (operationalised as >400g); eat at least 3 portions
107 of wholegrain products daily (>50g); eat at least 1 portion of oily fish per week (>150g) and
108 eat less than 3 portions of red or processed meat per week (<450g)⁽²⁰⁾. The Healthy Eating
109 Index 2010 (HEI) was derived based on intakes of the following components: ratio of mono-
110 and polyunsaturated fatty acids to saturated fatty acids, protein, salt, "empty calories", refined
111 grains, seafood and plant protein, fruit, whole fruit, vegetables, greens and beans,
112 wholegrains, dairy products⁽²⁵⁾.

113

114 **Personalised feedback report**

115 Participants randomized to PN received personalised reports via email at baseline, month 3
116 and month 6 of the intervention based on diet, anthropometric measurements and physical
117 activity. Using information on the individual's intakes of nutrients, algorithms were used to
118 rank information on need for dietary change and to provide participants with 3 specific
119 dietary, food-based goals. For participants randomized to Level 2 and Level 3, the dietary
120 advice was also based on phenotypic data (Level 2) and phenotypic plus genotypic data
121 (Level 3). Reported intakes were compared with recommended intakes and determined to be
122 adequate, high or low. If intakes were too high or too low, contributing foods were identified
123 and specific messages developed to advise change in intake of those foods. Dietary intakes
124 relative to recommendations were illustrated using a three-colour sliding scale: green
125 representing "Good, no change recommended," amber representing "Improvement
126 recommended" and red representing "Improvement strongly recommended". For the

127 genotype-based information, risk was indicated using “Yes” or “No” according to whether
128 the participant did, or did not, carry the higher risk variant for each of the 5 nutrient-related
129 genes included in the study. Additionally, each report contained a personalized message from
130 the dietitian/ nutritionist to the participant. Further details of the protocol are provided
131 elsewhere ⁽¹⁵⁾.

132

133 **Anthropometric, socio-demographic and physical activity measures**

134 Detailed standardised online instructions were given for participants to self-measure and self-
135 report their body weight, height and waist circumference (WC) via the Food4Me website
136 (www.Food4me.org). Body mass index (BMI) was estimated from body weight and height.
137 Self-reported measurements were validated in a sub-sample of the participants ($n=140$) and
138 showed a high degree of reliability ⁽²⁶⁾. Physical activity levels (PALs) and time spent in
139 sedentary behaviours (SB) were estimated from triaxial accelerometers (TracmorD, Philips
140 Consumer Lifestyle, the Netherlands). Participants self-reported smoking habits and
141 occupation. Occupations were grouped according to the European classifications of
142 occupations and their salaries (the European wide average salary for each occupation was
143 compared to the mean overall salary. If the standard deviation of the salary was >0.5 they
144 were placed in group 1, between 0.5 to -0.5 were placed into group 2 and <-0.5 were placed
145 into group 3): Group 1: Professional and managerial (professionals; managers); Group 2:
146 Intermediate (Armed forces occupations; technicians and associate professionals; clerical
147 support workers); Group 3: Routine and manual (craft and related trades workers; plant and
148 machine operators and assemblers; service and sales workers; elementary occupations; skilled
149 agricultural, forestry and fishery workers) ^(27; 28). Categories for “Students” and “Retired and
150 unemployed” were added.

151

152 **Statistical analysis**

153 Data were analysed using Stata (version 13; StataCorp, College Station, TX, USA) and IBM
154 SPSS (V.22, IBM Corporation, Armonk, NY, USA). Clusters of dietary recommendations
155 were generated based on whether participants met the following 4 food group
156 recommendations at baseline and were coded as 0 or 1 accordingly: eat at least 5 portions of
157 fruit and vegetables every day (operationalised as $>400g$); eat at least 3 portions of
158 wholegrain products daily ($>50g$); eat at least 1 portion of oily fish per week ($>150g$) and eat

159 less than 3 portions of red or processed meat per week (<450g). Clusters were derived using
160 the SPSS Two Step cluster analysis procedure ⁽²⁹⁾. Small pre-clusters were generated based
161 on log-likelihood distance criterion (Step 1), and were merged into distinct groups using
162 agglomerative hierarchical clustering (Step 2). Automatic selection and the Bayesian
163 Information Criterion (BIC) were used to determine the optimal number of clusters.
164 Robustness and stability of the final clusters were re-evaluated by random ordering of cases
165 (four times). This clustering methodology identified the percentage of participants within
166 each cluster who met recommended intakes of each of the 4 food groups of public health
167 importance. Logistic regression was used to test for significant differences across categorical
168 variables and ANOVA was used for continuous variables. Tukey's pairwise comparisons
169 were used to test for significant differences between clusters. Analyses were adjusted for age,
170 sex, country, BMI, PAL and smoking, except when those (or related) variables were being
171 assessed i.e. analyses were not adjusted for BMI when assessing BMI, body weight or WC.
172 Results were deemed significant at $P<0.05$. To exclude extreme intakes of the food groups
173 used for clustering, the top and bottom 3SD of these intakes were excluded prior to
174 clustering.

175

176 **RESULTS**

177 Of the 5562 individuals who registered on the Food4Me website, 1607 were randomised into
178 the study and a total of 1480 provided baseline data on dietary intakes ⁽¹⁵⁾.

179

180 **Dietary adequacies across Food4Me cohort**

181 Recommended intakes for nutrients are summarised in Supplementary Table 1. On average,
182 50% of individuals met the recommendations for total fat (Supplementary Table 1). The
183 percentage of individuals who met the recommendations for saturated (SFA), mono- (MUFA)
184 and polyunsaturated fatty acids (PUFA) intake was 54, 24 and 36%, respectively
185 (Supplementary Table 1). Only 56% of individuals met the recommendation for carbohydrate
186 intake, whereas 91% of individuals had adequate protein intakes. Only 7 and 46% of
187 individuals met the recommendations for salt and dietary fibre intakes, respectively. Meeting
188 recommended micronutrient intakes ranged from 61% (folate) to 99% (vitamin B12;
189 Supplementary Table 1).

190 As summarised in **Supplementary Table 2**, approximately half (52%) of participants
191 reported consuming at least 5 portions of fruit and vegetables per day and 32% consumed at
192 least 1 portion of oily fish per week. Nearly three quarters (74%) of participants consumed
193 more than 3 servings of wholegrains per day and approximately half of participants (51%)
194 consumed less than 3 servings of red meat per week (>450g/week). 14% of individuals met
195 the recommendation for dairy product intake (>600g/day).

196

197 **Cluster characterization**

198 Clustering of individuals according to whether they met the recommendations for dairy
199 products, fruit and vegetable, oily fish, red meat and wholegrain intake at baseline did not
200 create clear clustering due to the low percentage of individuals who met the recommendation
201 for dairy products (2 clusters). Exclusion of dairy products as a clustering variable provided
202 improved clustering, as estimated by silhouette measure of cohesion and separation (average
203 silhouette: 0.3 vs 0.5; 4 clusters, **Supplementary Table 3**). Cluster one (C1) was the largest
204 (n=475) and was particularly characterised by individuals meeting the recommended intake
205 for oily fish (100% of individuals); 74 and 69% of C1 members met the recommendations for
206 wholegrains and fruit and vegetables, respectively, whereas only 46% met the
207 recommendation for red meat. Cluster 2 (C2; n=398) was the second largest and was
208 particularly characterised by all members meeting recommendations for wholegrains (100%)
209 and red meat (100%), only 50% met the recommendation for fruit and vegetables and no one
210 meeting the recommendation for oily fish. All individuals in cluster 3 (C3; n=348) met the
211 recommendation for wholegrains, but no one met the recommendation for oily fish, or red
212 meat, whereas only 48% met the recommended intake for fruit and vegetables. None of the
213 participants in Cluster 4 (C4; n=259) met the recommended intakes for either oily fish or
214 wholegrains; only 50 and 71% of C4 members achieved the recommended intakes for red
215 meat and fruit and vegetables, respectively (Supplementary Table 3).

216

217 **Dietary intakes by clusters**

218 Intakes of oily fish and fruit and vegetables were higher in C1 than in C2, C3 and C4
219 ($P<0.05$), and wholegrain intakes were higher in C1, C2 and C3 than in C4 (**Table 1**;
220 $P<0.05$). Red meat intake was lower in C1, C2 and C3 than in C4 ($P<0.05$). Intakes of fruit

221 juice, eggs, chicken, white fish, fish products, beans and lentils and low fat dairy products
222 were higher in C1 than C4, whereas intakes of non-wholegrain products were lower
223 ($P<0.05$). Participants in C2 consumed lower intakes of chips and pizza and fried foods than
224 C3 and C4 ($P<0.05$; Table 1). Total energy intake and energy intake to basal metabolic rate
225 ratio (EI: BMR) were higher in C1 than in C2 and C4 and higher in C3 than in C2 ($P<0.05$;
226 Table 1). Individuals in C1 derived higher percentages of energy intake from PUFA and
227 protein than those in C2 and C4 ($P<0.05$) and individuals in C2 higher percentage energy
228 from carbohydrates than participants in C3 and C4 ($P<0.05$). In contrast, individuals in C1
229 had lower percentage energy intakes from total fat and SFA than those in C4 ($P<0.05$) and
230 higher percentage energy intake from monounsaturated fatty acids (MUFA) than participants
231 in C2 and C3 ($P<0.05$). Subjects in C1 had lower percentage energy intake from sugar than
232 C2 ($P<0.05$). Participants in C1 consumed more dietary fibre and salt than those in C2 and
233 C4 ($P<0.05$).

234 More individuals in C1 met the recommendation for total fat intake (51%), SFA (62%),
235 PUFA (42%) and dietary fibre (56%) than C4 cluster members (**Supplementary Table 4**).
236 Fewer individuals in C1 met the recommendations for protein intake (86%) than those in C2
237 (97%) and C3 (93%). Furthermore, fewer individuals in C1 met the recommendation for salt
238 intake (5%) than C2 (11%) and C4 (17%; Table 4).

239

240 **Socio-demographic, anthropometric and health characteristic by clusters**

241 Individuals in C1 were on average 4.5 years older than C4 ($P<0.05$; **Table 2**). Body weight
242 was significantly lower in C1 than in C3, and lower in C2 compared with C3 and C4
243 ($P<0.05$). Individuals in C1 had 1.4kg/m^2 lower BMI and 5cm lower WC than participants in
244 C3 ($P<0.05$) and PAL was higher in C1 than C2 and C4 ($P<0.05$). 11% more individuals in
245 C4 wanted to lose weight than those in C1 ($P<0.05$; Table 2) and C4 was characterised by
246 more current smokers than C1 ($P<0.05$). 12% more individuals in C1 had a professional or
247 managerial occupation than C4, and similarly 7% more individuals had a manual occupation
248 in C4 compared with C1 ($P<0.05$; Table 2). No other significant differences were observed
249 (Table 2).

250

251 **Changes in Healthy Eating Index (HEI) by cluster after 6 months intervention**

252 Baseline and follow up HEI scores and their components are presented in **Table 3**. There
253 were no significant differences in changes in HEI between clusters for those randomised to
254 non-personalised dietary advice. In contrast, for individuals who received PN advice (based
255 on information of current diet alone or combined with information on phenotype and
256 genotype), changes in HEI differed between clusters ($P<0.001$). There were bigger
257 improvements in HEI for participants in C4 compared with C1 and C2 ($P<0.05$) and in C2
258 compared with C4 ($P<0.05$; Figure 1). There were no significant differences in changes in
259 HEI between clusters when PN was stratified by L1, L2 or L3 (data not shown).

260

261 **Sensitivity analyses**

262 Exclusion of participants with reported intakes more than 3 SD above or below the mean
263 dietary intakes of wholegrain, oily fish, red meat and fruit and vegetables revealed similar
264 clusters (**Supplementary Table 5**). The pattern of the main results remained the same, with
265 individuals in C3 and C4 making greater changes in HEI at month 6 than those in C1, and
266 participants in C4 compared with those in C2 ($P<0.05$).

267

268 **DISCUSSION**

269 **Main findings**

270 Based on our secondary analysis in the Food4Me PoP study, we identified four distinct
271 clusters of individuals according to their adherence to current European dietary
272 recommendations. Individuals in C1 and C2 met more dietary recommendations than those in
273 C3 and C4. Moreover, on average individuals in C1 and C2 had a healthier diet, lower BMI
274 and WC and smoked less compared with those in C3 and C4. When randomised to a 6-month
275 PN intervention, participants in C4 made the greatest improvements in their diets (as
276 estimated by HEI), compared with participants receiving non-personalised “one size fits all”
277 generalised advice. This is the first study to investigate clusters of adherence to European
278 dietary recommendations and to determine the responsiveness of cluster members to PN
279 advice.

280

281 **Comparison with other studies**

282 Previous studies have used cluster analysis to categorise individuals⁽³⁰⁾. We used cluster
283 analysis to categorise individuals based on their adherence to current European food-based

284 dietary guidelines at baseline for participants in the Food4Me intervention study. This
285 approach identified groups of individuals who differed in the number, and groupings, of
286 dietary recommendations they met. Clusters where more individuals met the
287 recommendations were characterised by being slightly older and in more highly educated
288 occupations, which is a well-established characteristic of healthy dietary clusters ⁽³¹⁾.

289 Clustering of dietary intakes and adequacies have been investigated in relation to several
290 health outcomes ^(7; 8; 32) and can be strong predictors of these outcomes ⁽³³⁾. A recent review of
291 dietary clusters and health outcomes by the USDA ⁽³⁴⁾ concluded that the strongest evidence
292 for an association between unhealthy dietary patterns and increased disease risk, is for
293 cardiovascular disease (CVD), followed by obesity and then type 2 diabetes. This USDA
294 review concluded that there was a lack of studies assessing dietary intakes at follow-up and
295 using a universal and quantitative indicator of dietary intake. Our study is in line with these
296 recommendations as we utilised the HEI, which is a validated estimate of dietary adequacy,
297 and we assessed dietary change using the same instrument at both baseline and follow-up.
298 Although more limited, some prospective and RCT studies have investigated the effect of
299 clustering on changes in health outcomes ^(12; 35; 36), and some studies have used adherence to
300 dietary recommendations to derive clusters ^(12; 13; 14; 37; 38). Dietary recommendations used in
301 studies included in the systematic review by the USDA ⁽³⁴⁾ varied according to the study, but
302 all included a measure of fruit and vegetable, wholegrains and meat intake.

303 To our knowledge, no previous research has evaluated the impact of clustering of dietary
304 recommendations on the response to a PN intervention. We observed that individuals in the
305 cluster where the fewest recommendations were met (C4) reported the biggest improvement
306 in HEI following PN intervention but there were no differences between clusters in response
307 to conventional, non-personalised dietary advice. Given that adverse lifestyle behaviours and
308 the prevalence and risk of death from obesity-related diseases are strongly socioeconomically
309 patterned ⁽³⁹⁾, it is important that appropriate interventions are targeted to those most in need
310 of improved lifestyle. Whilst research on the development and implementation of PN
311 interventions and their effects on changing diets is in its infancy ⁽⁴⁰⁾, the findings from the
312 present study provide encouragement that PN interventions can be more effective than
313 current “one size fits all” interventions and that they may be particularly effective amongst
314 individuals with the poorest diets. There have been concerns that PN may be taken up only by
315 the ‘worried well’ ⁽⁴¹⁾, who already have adequate dietary intakes. However, our findings
316 suggest that PN is most effective in people who have the least adequate diets, and therefore

317 the greatest need for improvement in dietary intakes with the potential for significant
318 reductions in disease risk.

319

320 **Strengths and limitations**

321 The present study had a number of strengths. Our findings are derived from a relatively large
322 number of participants who were broadly representative of European adults from 7 different
323 European countries. The Food4Me RCT collected extensive information on anthropometrics,
324 physical activity and socio-demographic and health-related data, which contributed to
325 detailed characterization of participants in the clusters. Our study design allowed us to
326 estimate changes in dietary intakes using the same validated instrument at baseline and at
327 month 6. Furthermore, we quantified responses using the HEI, which has been shown to be
328 an effective indicator of overall diet quality ⁽²⁵⁾ and, therefore, a better measure of overall
329 dietary change than outcomes based on single foods or nutrients.

330 A limitation of the study is that our data were self-reported via the internet, which may have
331 introduced measurement error. However, the validity of internet-based, self-reported
332 anthropometric data is high ⁽⁴²⁾ and has been confirmed in the present study ⁽²⁶⁾. We were not
333 able to include dairy products as a dietary recommendation in the present analyses due to so
334 few individuals meeting the recommendation. However, dairy products do not have a
335 recommended intake in the UK and so habitual diets would not necessarily be expected to
336 comply with this recommendation, even if they were very health conscious. Dietary intakes
337 were estimated by a FFQ, which is known to be subject to misreporting error ⁽⁴³⁾ but this was
338 minimised by validating our FFQ against a 4-day weighed food record ⁽¹⁸⁾. Moreover, our
339 estimation of dietary change was based on the HEI, which is a validated indicator of overall
340 diet ⁽²⁵⁾, and which may be less susceptible to reporting errors than approaches measuring
341 change in specific nutrients or individual foods. Our study participants were almost solely
342 Caucasian – thus, further research in wider ethnicity groups is required to generalise our
343 findings to other populations. One of the primary aims of the Food4Me PoP study was to
344 evaluate change in intakes of food groups across 4 treatment arms. Thus, although the present
345 study is a secondary analysis of these data, clustering was based on how individuals adhered
346 to food group recommendations and included 4 clusters. As a result, our analyses are likely to
347 be powered to detect differences between clusters.

348

349 **Implications of findings**

350 Our findings suggest that the efficacy of PN in modifying dietary intakes depends on the
351 clustering of adherence to dietary recommendations, with those with the poorest diets
352 benefiting most from the PN intervention. As a result, the implementation of PN-based
353 interventions in individuals with the least healthy diets may help to address health
354 inequalities. Understanding the characteristics of individuals within coherent clusters which
355 are linked with their responsiveness to interventions may help in the design and
356 implementation of more effective health promotion actions. Future PN interventions may
357 benefit from tailoring PN advice based on clustering of overall dietary behaviours rather than
358 on single nutrients or foods.

359

360 **Conclusions**

361 We identified four distinct clusters of individuals based on adherence to current food-based
362 dietary recommendations. The cluster where the fewest recommendations were met (C4)
363 reported significantly greater improvements in their diets (as estimated by the HEI) following
364 a 6-month trial of PN, whereas there was no difference between clusters for those randomized
365 to the Control, non-personalised dietary intervention.

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FIGURE LEGENDS

Figure 1 Changes from baseline to month 6 in Healthy Eating Index by clusters of adherence to recommendations at baseline

Values represent predicted means and SE. Models were adjusted for age, sex, body mass index, physical activity level, smoking habits and country and Posthoc Tukey's tests was used to test for significant differences between clusters (C); C4>C1 ($P<0.001$), C3>C1 ($P=0.005$)

Table 1 Food and nutrient and intakes by participants by clusters of adherence to recommendations at baseline

	Clusters								P*
	1 (n=475)		2 (n=398)		3 (n=348)		4 (n=259)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Dietary recommendations, g/d									
Oily fish	48	32 ^{2,3,4}	8	7	10	7	8	7	<0.001
Wholegrains	183	182 ^{2,4}	216	184 ^{3,4}	205	165 ⁴	22	16	<0.001
Red meat	85	80.9 ^{2,3,4}	30	20 ^{3,4}	119	53 ⁴	84	96	<0.001
Fruit and vegetables	610	371 ^{2,3,4}	470	303 ^{3,4}	456	288	339	218	<0.001
Other food intakes, g/d									
Fruit Juice	117	181 ^{3,4}	114	165	94	144	76	108	0.008
Non-wholemeal	116	140 ^{2,4}	78	76 ⁴	114	103 ⁴	149	189	<0.001
Eggs	41	41 ^{2,3}	22	24	31	47	30	51	<0.001
Chicken, grilled or roast	36	37 ^{2,3,4}	17	21 ³	28	25	25	27	<0.001
White fish	26	26 ^{2,3,4}	10	14	13	14	11	14	<0.001
Fish products	19	30 ^{2,4}	10	11 ³	14	16	13	15	<0.001
Beans and lentils	30	40 ^{2,3}	15	24	16	27	22	28	<0.001
Butter	4	9 ³	6	11 ³	9	18 ⁴	5	12	0.005
Low fat dairy	293	296 ^{2,3,4}	217	203	221	212	173	219	<0.001
High fat dairy	64	120	60	119	83	113	83	204	0.44
Sugar sweetened beverages	36	176	18	55	40	139	41	84	0.39
Low calorie soft drinks	66	194	46	154	80	239	72	190	0.53
Added sugar	4	9	4	11	5	13	7	13	0.11
Chocolate and sweets	21	37	19	23	26	61	17	26	0.10
Cakes	22	31	18	25	20	25	22	39	0.08
Biscuits	30	55	21	37	35	88	27	55	0.38
Ice-cream	7	19	6	11	7	12	7	13	0.62
Pastries	8	34	4	6	6	10	10	39	0.49
Crisps	4	10	3	5 ³	5	10	4	8	0.06
Chips and pizza	30	41	24	22 ^{3,4}	35	30	34	35	0.001
Fried foods	33	52 ²	21	28 ^{3,4}	34	35	33	30	0.047
Nutrient intake									
Total energy, kcal/d	2870	1219 ^{2,4}	2218	745 ³	2855	1065 ⁴	2106	978	<0.001
EI:BMR ratio	1.9	0.7 ^{2,4}	1.5	0.5 ³	1.8	0.6 ⁴	1.4	0.6	<0.001
Total fat, % energy	36.0	5.7 ^{2,4}	34.1	5.6 ^{3,4}	36.4	5.5	37.9	6.6	<0.001
SFA, % energy	13.4	2.8 ^{3,4}	13.6	3.3 ^{3,4}	14.9	3.0	15.3	3.3	<0.001
MUFA, % energy	14.2	3.2 ^{2,3}	12.6	2.8 ^{3,4}	13.6	2.6 ⁴	14.8	3.5	<0.001
PUFA, % energy	6.0	1.4 ^{2,4}	5.7	1.4	5.6	1.3	5.5	1.7	0.003
Protein, % energy	18.3	4.1 ^{2,3,4}	15.5	3.2 ^{3,4}	17.0	2.9	17.3	3.7	<0.001

Carbohydrate, % energy	44.5	7.5 ^{2,3}	49.6	7.0 ^{3,4}	45.6	6.4	43.7	8.3	< 0.001
Sugars, % energy	21.0	5.9 ²	22.5	6.1 ^{3,4}	19.8	5.6	20.8	5.9	< 0.001
Dietary fibre, g/d [†]	34.0	15.8 ^{2,4}	30.2	14.4 ⁴	31.7	12.8 ⁴	18.7	8.2	< 0.001
Salt, g/d [†]	8.3	4.0 ^{2,4}	6.1	2.7 ³	8.7	3.6 ⁴	5.9	3.6	< 0.001

Values represent means and SD

*, ANOVA were adjusted for age, sex, BMI, PAL, smoking habits and country; Posthoc Tukey tests were performed to test for significant differences between clusters Superscript numbers denote where the differences lie across the clusters. For example, 1 means significantly different from cluster 1.

[†], P values are also adjusted for total energy intake.

Table 2 Socio-demographic characteristics of participants by clusters of adherence to recommendations at baseline

	Clusters								P*
	1 (n=475)		2 (n=398)		3 (n=348)		4 (n=259)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Age, years	41.2	12.7 ^{2,3}	39.2	14.2 ⁴	41.2	12.7 ⁴	36.7	11.5	< 0.001
Female, %	56.0		67.3		47.4		64.1		0.79
Ethnicity, %	95.6		96.5		97.7		98.1		0.16
Occupation, %	44.2 ⁴		37.8		39.4		32.2		0.014
Professional and managerial	25.9		22.4		28.5		28.7		0.16
Intermediate occupations	7.4 ⁴		6.8		12.9		14.3		0.006
Routine and manual	13.5		21.7		9.5		14.7		0.18
Student	9.1		11.3		9.8		10.1		0.38
Not currently working									
Anthropometrics									
Body weight, kg	74.6	15.1 ³	70.5	15.0 ^{3,4}	80.3	16.0 ⁴	74.1	16.3	< 0.001
BMI, kg/m ²	25.4	4.4 ^{2,3}	24.1	4.4 ^{3,4}	26.8	4.9	26.0	5.7	< 0.001
Waist circumference, cm	85.4	13.0 ³	81.8	13.2	90.4	14.1	85.9	14.1	< 0.001
Physical activity									
PAL	1.8	0.2 ^{2,4}	1.7	0.2 ³	1.8	0.2 ⁴	1.7	0.2	< 0.001
SB, min/d	746	73	742	77	750	76	744	7	0.96
Dietary conditions, %									
Want to lose weight	46.1 ⁴		41.2		48.6		57.5		0.013
Restricted diet	6.1		11.6		3.7		5.8		0.47
Medication use, %									
Prescribed medication	26.1		35.7		29.9		27.0		0.79
Non-prescribed medication	8.6		10.6		9.2		11.2		0.18
Health and disease									
Current smoker, %	9.8 ⁴		9.0		10.3		22.0		0.005
Total cholesterol, mmol/L	4.6	0.9	4.5	1.0	4.7	1.0	4.6	0.9	0.09
High blood pressure, %	8.2		7.0		9.8		5.8		0.89
Heart disease, %	2.1		1.8		0.6		1.2		0.17

Values represent means and SD or percentages; PAL, physical activity level; SB, sedentary behaviour

*, ANOVA and logistic regression were used to test for significant differences across clusters in continuous and categorical variables, respectively. Analyses were adjusted for age, sex, BMI, PAL, smoking habits and country.

Post hoc Tukey tests (continuous data) and logistic regression (categorical) were used to test for significant differences between clusters. Superscripts denote where the differences lie across the clusters. For example, 2 means significantly different from cluster 2.

Table 3 Healthy Eating Index (HEI) score and its constituents at baseline and month 6 by clusters of adherence to recommendations

	Cluster								P†
	1 (n=475)		2 (n=398)		3 (n=348)		4 (n=259)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Baseline score									
Total HEI	53.3	8.9 ^{2,3,4}	50.5	8.9 ^{3,4}	47.5	8.9 ⁴	41.8	10.1	<0.001
Fatty acid ratio*	3.2	2.4 ^{2,3,4}	2.2	2.4 ^{3,4}	1.7	1.7	2.0	2.0	<0.001
Protein	3.7	0.7 ^{2,3,4}	3.2	0.6 ^{3,4}	3.5	0.6	3.5	0.7	<0.001
Salt	0.1	0.5	0.1	0.7	0.1	0.6	0.1	0.6	0.002
Empty calories	8.8	4.0 ²	7.7	4.3	8.5	3.8	7.5	4.1	0.012
Refined grains	6.1	3.7 ^{2,3,4}	4.8	3.7	4.4	3.7	4.7	4.0	<0.001
Seafood and plant protein	5.0	0.2 ^{2,3,4}	4.5	1.0	4.3	1.1	4.4	1.1	<0.001
Fruit	3.8	1.3 ³	3.8	1.4 ³	3.3	1.5	3.3	1.5	<0.001
Whole fruit	4.2	1.3 ^{3,4}	4.1	1.3 ^{3,4}	3.6	1.5	3.6	1.6	<0.001
Vegetables	2.5	1.1 ^{3,4}	2.3	1.1 ^{3,4}	2.0	0.9	2.1	1.1	<0.001
Greens and beans	4.2	1.1 ^{2,3,4}	3.8	1.3 ³	3.5	1.3	3.7	1.4	<0.001
Wholegrains	7.3	3.5	9.5	1.2	8.8	1.9	2.9	2.2	<0.001
Dairy products	4.7	2.6 ^{2,3,4}	4.7	2.7 ⁴	4.3	2.2 ⁴	4.4	2.7	0.27
Follow up score									
Total HEI	55.7	9.1 ^{1,3,4}	53.3	9.6 ⁴	51.4	8.7	48.0	10.3	<0.001
Fatty acid ratio ¹	3.8	2.6 ^{2,3,4}	3.1	2.7 ³	2.5	2.1	2.6	2.2	<0.001
Protein	3.8	0.7 ^{2,3,4}	3.3	0.6 ^{3,4}	3.6	0.6	3.6	0.6	<0.001
Salt	0.1	0.6	0.2	0.9 ³	0.1	0.6	0.1	0.6	0.002
Empty calories	8.7	4.0 ²	7.4	4.1	8.8	4.0	8.1	4.1	0.002
Refined grains	6.2	3.8 ⁴	5.4	3.8	5.1	3.8	4.9	3.8	0.004
Seafood and plant protein	5.0	0.2 ^{2,3}	4.7	0.8	4.6	1.0	4.7	±0.9	<0.001
Fruit	4.1	1.3	4.2	1.2 ³	3.7	1.4	3.7	±1.5	0.009
Whole fruit	4.4	1.2	4.4	1.1	4.1	1.4	4.0	±1.5	0.023
Vegetables	2.8	1.2 ^{3,4}	2.7	1.3 ^{3,4}	2.3	1.0	2.4	1.0	<0.001
Greens and beans	4.3	1.0 ^{2,3}	4.0	1.2	3.9	1.2	4.1	1.2	0.001
Wholegrains	7.9	3.1 ^{2,3,4}	9.2	1.9 ⁴	8.5	2.7 ⁴	5.5	3.7	<0.001
Dairy products	4.8	2.7	4.7	2.8	4.4	2.3	4.5	2.6	0.52

Values represent means and SD.

*, Fatty acid ratio is the ratio of unsaturated fatty acids (mono- and polyunsaturated fatty acids) to saturated fatty acids

† ANOVA were used to test for significant differences across clusters. Models were adjusted for age, sex, body mass index, physical activity level, smoking habits and country. Posthoc Tukey's tests used to test for significant differences between clusters. Superscript numbers denote where the differences lie across the clusters relative to the reference category (1). For example, 2 means significantly different from cluster 2.

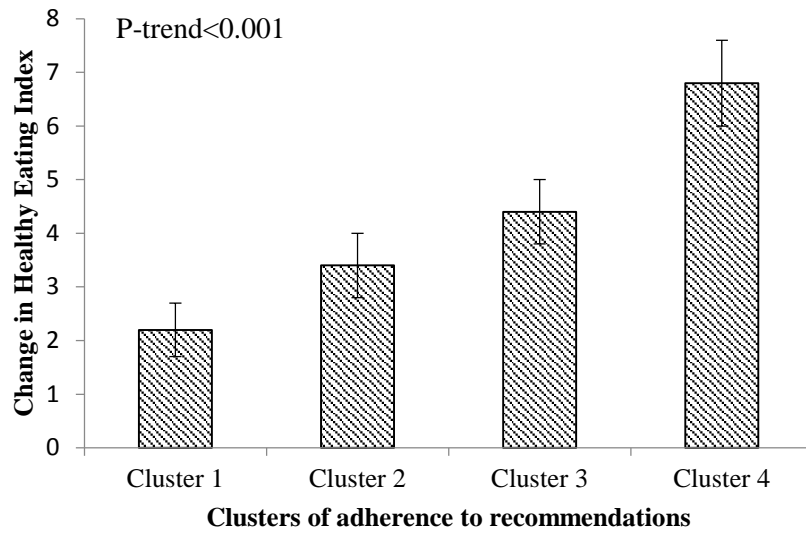


Figure 1

Supplementary Table 1. Summary of criteria for assessing dietary intakes*

			Deficient	Adequate	In excess
Food groups					
Fruit and vegetables, g/d			<400	≥400	NA
Wholegrains, g/d			<50	≥50	NA
Dairy products, g/d			<600	≥600	NA
Oily fish, g/wk			<150	≥150	NA
Red meat, g/wk			NA	≤450	>450
Nutrients					
Protein, g/kg body weight			<0.66	≥0.66 & ≤2.4	>2.4
Carbohydrate, % of total energy			<45	45-65	>65
Total fat, % of total energy			<20	20-35	>35
Monounsaturated, % of total energy			<15	15-20	>20
Polyunsaturated, % of total energy			<6	6-11	>11
Saturated fat, % of total energy			<10	≥10 & ≤15	>15
Salt, g/d		18-50yrs	≤3.75	>3.75 & ≤5.75	>5.75
		51-70yrs	≤3.25	>3.25 & ≤5.75	>5.75
		>70yrs	<3	≥3 & <5.75	>5.75
Omega-3, % of total energy			<0.2	≥0.2 & <0.6	≥0.6
Fibre, g/d	Males	18-50yrs	<28	≥28 & <38	≥38
		>50yrs	<20	≥20 & <30	≥30
	Females	18-50yrs	<15	≥15 & <25	≥25
		>50yrs	<14	≥14 & <21	≥21
Calcium, mg/d	Males	18-70yrs	<800	≥800 & ≤2500	>2500
		>70yrs	<1000	≥1000 & ≤2500	>2500
	Females	18-50yrs	<800	≥800 & ≤2500	>2500
		>50yrs	<1000	≥1000 & ≤2500	>2500
Iron, mg/d	Males	>18yrs	≥4 & <6	≥6.0 & ≤45	>45
	Females	18-50yrs	<8.1	≥8.1 & ≤45	>45
		>50yrs	<5	≥5 & ≤45	>45
Vitamin A, µg/d	Males		<625	≥625 & ≤3000	>3000
	Females		<500	≥500 & ≤3000	>3000
Folate, µg/d			<320	≥320 & ≤1000	>1000
Thiamin, mg/d	Males		<0.8	≥0.8 & ≤1.0	>1.0
	Females		<0.7	≥0.7 & ≤0.9	>0.9
Riboflavin, mg/d	Males		<0.9	≥0.9 & ≤1.1	>1.1
	Females		<0.7	≥0.7 & ≤0.9	>0.9
Vitamin B12, µg/d			<1.6	≥1.6 & ≤2.0	>2.0
Vitamin C, mg/d	Males		<75	≥75 & ≤2000	>2000
	Females		<60	≥60 & ≤2000	>2000

*, Cut-offs were used to deliver personalized dietary advice during the intervention (20-23)

Supplementary Table 2. Percentage of individuals meeting current European dietary recommendations at baseline

	Meet recommendation	
	Percentage	95% CI
Food group intake, %		
Fruit and vegetables	52.0	45.7-58.1
Oily fish	32.1	18.7-49.3
Red meat	50.5	39.8-61.3
Wholegrains	74.2	51.9-88.5
Dairy products	13.7	9.2-19.9
Nutrient intake, %		
Total fat	50.4	43.5-57.3
Saturated fat	54.3	45.2-63.0
Mono-unsaturated fat	24.3	16.0-35.0
Poly-unsaturated fat	36.2	28.2-45.1
Protein	91.1	87.7-93.6
Carbohydrate	55.6	47.4-63.6
Salt	7.4	3.6-14.8
Dietary fibre	45.5	35.9-55.6
Calcium	73.8	65.8-80.5
Folate	61.4	48.5-72.8
Iron	95.1	91.8-97.1
Riboflavin	95.5	89.9-98.0
Thiamine	97.1	92.6-98.9
Vitamin A	83.7	77.8-88.3
Vitamin B12	98.6	96.9-99.4
Vitamin C	90.1	84.7-93.8

Values represent percentages (95% CI) of individuals meeting current European dietary recommendations (20-23)

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Supplementary Table 3. Description of dietary clusters and the percentage of individuals within each cluster who met the dietary recommendations at baseline (met recommended intake: ✓; did not meet recommended intake: ✗)

	Clusters			
	1 (n=475)	2 (n=398)	3 (n=348)	4 (n=259)
Total, n	475	398	348	259
Food group				
Oily fish	✓ (100%)	✗ (100%)	✗ (100%)	✗ (100%)
Wholegrains	✓ (74.1%)	✓ (100%)	✓ (100%)	✗ (100%)
Red meat	✗ (53.7%)	✓ (100%)	✗ (100%)	✓ (50.2%)
Fruit and vegetables	✓ (69.3%)	✗ (50.3%)	✗ (52.3%)	✗ (70.7%)

Values represent the percentage of individuals meeting the following recommendations: Fruit and vegetables >5 servings/day; Oily fish >1 serving/week; Wholegrains >3 servings/day; Red meat <3 servings/week (20-23)

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Supplementary Table 4 Percentage of individuals meeting nutrient-based guidelines by clusters of adherence to recommendations at baseline*

	Clusters				P†
	1 (n=475)	2 (n=398)	3 (n=348)	4 (n=259)	
Total fat, % energy	50.5 ^{2,4}	58.5	50.0	38.2	0.046
SFA, % energy	62.1 ^{3,4}	53.5	50.6	46.0	<0.001
MUFA, % energy	29.1	12.6	22.1	36.3	0.68
PUFA, % energy	42.1 ^{3,4}	36.2	32.2	30.9	0.005
Protein, g/kg/d	85.9	96.5	93.4	89.2	0.99
Carbohydrate, % energy	46.5	75.6	54.0	43.6	0.93
Dietary fibre, g/d	56.2 ⁴	50.8	50.3	11.6	<0.001
Salt, g/d	4.6 ^{2,4}	11.3	0.0	16.6	0.034

Values represent percentages of individuals that meet the dietary guidelines:

*, Dietary recommendations: Total fat: 20-35 % energy; SFA: 10-15% energy; MUFA: 15-20% energy; PUFA: 6-11% energy; protein: 0.66-2.4g/kg/day; carbohydrate: 45-65% energy; dietary fibre: males (18-50yrs \geq 38g/day; >50yrs \geq 30g/day) and females (18-50yrs \geq 25g/day; >50yrs \geq 21g/day); salt: 18-50yrs \leq 3.75g/day; 51-70yrs \leq 3.25g/day; >70yrs \leq 3g/day

†, Logistic regression was used to test for significant differences across and between clusters (cluster 1 was used as the base category) ^(20; 21; 22; 23).

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Supplementary Table 5 Percentage of individuals meeting dietary recommendations by clusters of adherence to recommendations after exclusion of 3SD of each of the four dietary components at baseline (met recommended intake: ✓; did not meet recommended intake: ✗)

	Clusters			
	1 (n=475)	2 (n=398)	3 (n=348)	4 (n=259)
Total, n	439	341	328	275
Food group				
Oily fish	✓ (93.6%)	✗ (100%)	✗ (100%)	✗ (100%)
Fruit and vegetables	✓ (68.8%)	✓ (100%)	✗ (86.3%)	✗ (100%)
Red meat	✗ (55.6%)	✓ (53.7%)	✓ (100%)	✗ (100%)
Wholegrains	✓ (68.8%)	✓ (100%)	✓ (86.3%)	✓ (100%)

Values represent the percentage of individuals meeting the following recommendations: Fruit and vegetables >5 servings/day; Oily fish >1 serving/week; Wholegrains >3 servings/day; Red meat <3 servings/week (20-23)