**Title**

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


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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.

**Abstract (words count=250)**

**Objective**

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

**Design**

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

**Setting**

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

**Subjects**

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

**Results**

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

**Conclusions**

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

**Trial registration** – Clinicaltrials.gov NCT01530139

**Key Words** – Clustering; personalised nutrition; dietary recommendations; healthy eating index

## INTRODUCTION

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

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

## METHODS

### Study design and population

The Food4Me study was a 6-month, 4-arm, internet-based, RCT in 1607 individuals conducted across 7 European countries [15]. Participants were recruited via the Food4Me website [16] to emulate a web-based PN service. This was aided by local and national advertising of the study via the Internet, radio, newspapers, posters, e-flyers, social media and word of mouth. Recruitment took place between August 2012 and August 2013 in the following sites: University College Dublin (Ireland), Maastricht University (The Netherlands), University of Navarra (Spain), Harokopio University (Greece), University of Reading (United Kingdom, UK), National Food and Nutrition Institute (Poland), Technical University of Munich (Germany). The Research Ethics Committees at each University or Research Centre delivering the intervention granted ethical approval for the study. 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.

**Intervention arms**

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

**Screening questionnaires and dietary intakes**

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

## Personalised feedback report

Participants randomized to PN received personalised reports via email at baseline, month 3 and month 6 of the intervention based on diet, anthropometric measurements and physical activity. Using information on the individual's intakes of nutrients, algorithms were used to rank information on need for dietary change and to provide participants with 3 specific dietary, food-based goals. For participants randomized to Level 2 and Level 3, the dietary advice was also based on phenotypic data (Level 2) and phenotypic plus genotypic data (Level 3). Reported intakes were compared with recommended intakes and determined to be adequate, high or low. If intakes were too high or too low, contributing foods were identified and specific messages developed to advise change in intake of those foods. Dietary intakes relative to recommendations were illustrated using a three-colour sliding scale: green representing "Good, no change recommended," amber representing "Improvement recommended" and red representing "Improvement strongly recommended". For the genotype-based information, risk was indicated using “Yes” or “No” according to whether the participant did, or did not, carry the higher risk variant for each of the 5 nutrient-related genes included in the study. Additionally, each report contained a personalized message from the dietitian/ nutritionist to the participant. Further details of the protocol are provided elsewhere [15].

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

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

**Statistical analysis**

Data were analysed using Stata (version 13; StataCorp, College Station, TX, USA) and IBM SPSS (V.22, IBM Corporation, Armonk, NY, USA). Clusters of dietary recommendations were generated based on whether participants met the following 4 food group recommendations at baseline and were coded as 0 or 1 accordingly: eat at least 5 portions of fruit and vegetables every day (operationalised as >400g); eat at least 3 portions of wholegrain products daily (>50g); eat at least 1 portion of oily fish per week (>150g) and eat less than 3 portions of red or processed meat per week (<450g). Clusters were derived using the SPSS Two Step cluster analysis procedure [29]. Small pre-clusters were generated based on log-likelihood distance criterion (Step 1), and were merged into distinct groups using agglomerative hierarchical clustering (Step 2). Automatic selection and the Bayesian Information Criterion (BIC) were used to determine the optimal number of clusters. Robustness and stability of the final clusters were re-evaluated by random ordering of cases (four times). This clustering methodology identified the percentage of participants within each cluster who met recommended intakes of each of the 4 food groups of public health importance. Logistic regression was used to test for significant differences across categorical variables and ANOVA was used for continuous variables. Tukey's pairwise comparisons were used to test for significant differences between clusters. Analyses were adjusted for age, sex, country, BMI, PAL and smoking, except when those (or related) variables were being assessed i.e. analyses were not adjusted for BMI when assessing BMI, body weight or WC. Results were deemed significant at $P<0.05$. To exclude extreme intakes of the food groups used for clustering, the top and bottom 3SD of these intakes were excluded prior to clustering.

## RESULTS

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

### Dietary adequacies across Food4Me cohort

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

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

## Cluster characterization

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

## Dietary intakes by clusters

Intakes of oily fish and fruit and vegetables were higher in C1 than in C2, C3 and C4 ($P<0.05$), and wholegrain intakes were higher in C1, C2 and C3 than in C4 (**Table 1**; $P<0.05$). Red meat intake was lower in C1, C2 and C3 than in C4 ($P<0.05$). Intakes of fruit juice, eggs, chicken, white fish, fish products, beans and lentils and low fat dairy products were higher in C1 than C4, whereas intakes of non-wholegrain products were lower (*P*<0.05). Participants in C2 consumed lower intakes of chips and pizza and fried foods than C3 and C4 (*P*<0.05; Table 1). Total energy intake and energy intake to basal metabolic rate ratio (EI: BMR) were higher in C1 than in C2 and C4 and higher in C3 than in C2 (*P*<0.05; Table 1). Individuals in C1 derived higher percentages of energy intake from PUFA and protein than those in C2 and C4 (*P*<0.05) and individuals in C2 higher percentage energy from carbohydrates than participants in C3 and C4 (*P*<0.05). In contrast, individuals in C1 had lower percentage energy intakes from total fat and SFA than those in C4 (*P*<0.05) and higher percentage energy intake from monounsaturated fatty acids (MUFA) than participants in C2 and C3 (*P*<0.05). Subjects in C1 had lower percentage energy intake from sugar than C2 (*P*<0.05). Participants in C1 consumed more dietary fibre and salt than those in C2 and C4 (*P*<0.05).

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

### Socio-demographic, anthropometric and health characteristic by clusters

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

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

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

**Sensitivity analyses**

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

## DISCUSSION

**Main findings**

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

**Comparison with other studies**

Previous studies have used cluster analysis to categorise individuals [30]. We used cluster analysis to categorise individuals based on their adherence to current European food-based dietary guidelines at baseline for participants in the Food4Me intervention study. This approach identified groups of individuals who differed in the number, and groupings, of dietary recommendations they met. Clusters where more individuals met the recommendations were characterised by being slightly older and in more highly educated occupations, which is a well-established characteristic of healthy dietary clusters [31].

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

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

**Strengths and limitations**

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

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

## Implications of findings

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

## Conclusions

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

## REFERENCES

1. Ng M, Fleming T, Robinson M *et al.* (2014) Global, regional, and national prevalence of overweight and obesity in children and adults during 1980-2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet* **384**, 766-781.
2. Hill JO, Wyatt HR, Peters JC (2012) Energy Balance and Obesity. *Circulation* **126**, 126-132.
3. NHS (2015) Livewell-Healthy living for everyone. http://www.nhs.uk/Livewell/Pages/Livewellhub.aspx
4. Hood L, Friend SH (2011) Predictive, personalized, preventive, participatory (P4) cancer medicine. *Nat Rev Clin Oncol* **8**, 184-187.
5. Nielsen DE, El-Sohemy A (2014) Disclosure of Genetic Information and Change in Dietary Intake: A Randomized Controlled Trial. *PLoS ONE* **9**, e112665.
6. Berrigan D, Dodd K, Troiano RP *et al.* (2003) Patterns of health behavior in U.S. adults. *Prev Med* **36**, 615-623.
7. Leech R, McNaughton S, Timperio A (2014) The clustering of diet, physical activity and sedentary behavior in children and adolescents: a review. *International Journal of Behavioral Nutrition and Physical Activity* **11**, 4.
8. Newby PK, Muller D, Hallfrisch J *et al.* (2003) Dietary patterns and changes in body mass index and waist circumference in adults. *The American Journal of Clinical Nutrition* **77**, 1417-1425.
9. Moore L, Singer M, Bradlee ML *et al.* (2015) Adolescent dietary intakes predict cardiometabolic risk clustering. *Eur J Nutr*, 1-8.
10. Khaw K-T, Wareham N, Bingham S *et al.* (2008) Combined Impact of Health Behaviours and Mortality in Men and Women: The EPIC-Norfolk Prospective Population Study. *PLoS Med* **5**, e12.
11. Dam RMv, Li T, Spiegelman D *et al.* (2008) *Combined impact of lifestyle factors on mortality: prospective cohort study in US women*. vol. 337.
12. Kesse-Guyot E, Castetbon K, Estaquio C *et al.* (2009) Association Between the French Nutritional Guideline-based Score and 6-Year Anthropometric Changes in a French Middle-aged Adult Cohort. *American Journal of Epidemiology* **170**, 757-765.
13. Chiuve SE, Fung TT, Rexrode KM *et al.* (2011) Adherence to a low-risk, healthy lifestyle and risk of sudden cardiac death among women. *JAMA : the journal of the American Medical Association* **306**, 62-69.
14. Zamora D, Gordon-Larsen P, He K *et al.* (2011) Are the 2005 Dietary Guidelines for Americans Associated With Reduced Risk of Type 2 Diabetes and Cardiometabolic Risk Factors?: Twenty-year findings from the CARDIA study. *Diabetes Care* **34**, 1183-1185.
15. Celis-Morales C, Livingstone KM, Marsaux CFM *et al.* (2015) Design and baseline characteristics of the Food4Me study: a web-based randomised controlled trial of personalised nutrition in seven European countries. *Genes Nutr* **10**, 450.
16. Food4Me (2016) An integrated analysis of opportunities and challenges for personalised nutrition. http://www.food4me.org/ (accessed 12th February 2016)
17. Forster H FR, Gallagher C, O'Donovan CB, Woolhead C, Walsh MC, Macready AL, Lovegrove JA, Mathers JC, Gibney MJ, Brennan L, Gibney ER (2014) Online Dietary Intake Estimation: The Food4Me Food Frequency Questionnaire. *J Med Internet Res* **16**, e150.
18. Fallaize R, Forster H, Macready AL *et al.* (2014) Online Dietary Intake Estimation: Reproducibility and Validity of the Food4Me Food Frequency Questionnaire Against a 4-Day Weighed Food Record. *J Med Internet Res* **16**, e190.
19. Food Standards Agency (2002) *McCance and Widdowson's The Composition of Foods*. Sixth summary edition ed*.* Cambridge: Royal Society of Chemistry.
20. Celis-Morales C, Livingstone K, Marsaux CM *et al.* (2014) Design and baseline characteristics of the Food4Me study: a web-based randomised controlled trial of personalised nutrition in seven European countries. *Genes Nutr* **10**, 1-13.

21. Institute of Medicine (2005) Dietary Reference Intakes for energy, Carbohydrate, Fibre, Fat, Fatty acids, Cholesterol, Protein, and Amino acids 2005. http://www.nap.edu/openbook.php?isbn=0309085373 (accessed 24th March 2015)
22. Institute of Medicine (2011) Dietary Reference Intakes Tables and Applications 2011. http://www.iom.edu/Activities/Nutrition/SummaryDRIs/DRI-Tables.aspx (accessed 24th March 2015)
23. World Health Organisation (2007) *Protein and Amino acid requirements in Human Nutrition. Report of a Joint WHO/FAO/UNU Expert Consultation (WHO Technical Report Series 935)*.
24. World Health Organisation (2010) Food and Agriculture Organisation of the United Nations (FAO) report of an expert consultation on fats and fatty acids in human nutrition. http://www.who.int/nutrition/publications/nutrientrequirements/fatsandfattyacids_humannutrition/en/ (accessed 30th March 2016)
25. Guenther PM, Casavale KO, Reedy J *et al.* (2013) Update of the Healthy Eating Index: HEI-2010. *Journal of the Academy of Nutrition and Dietetics* **113**, 569-580.
26. Celis-Morales C, Forster H, O'Donovan C *et al.* (2014) Validation of Web-based self-reported socio-demographic and anthropometric data collected in the Food4Me Study. *Proc Nutr Soc* **73**, null-null.
27. European Commission (2015) European skills, competences, qualifications and occupations. https://ec.europa.eu/esco/web/guest/hierarchybrowser/-/browser/Occupation (accessed 1st April 2015)
28. European Commission (2015) Mean annual earnings by sex, age and occupation. http://ec.europa.eu/eurostat/web/products-datasets/-/earn_ses_agt28 (accessed 27th March 2015)
29. Tom C, DongPing F, John C *et al.* (2001) A robust and scalable clustering algorithm for mixed type attributes in large database environment. In *Proceedings of the seventh ACM SIGKDD international conference on Knowledge discovery and data mining*. San Francisco, California: ACM.
30. Ocké MC (2013) Evaluation of methodologies for assessing the overall diet: dietary quality scores and dietary pattern analysis. *Proc Nutr Soc* **72**, 191-199.
31. Kant AK (2004) Dietary patterns and health outcomes. *J Am Diet Assoc* **104**, 615-635.
32. Ma Y, Bertone ER, Stanek EJ *et al.* (2003) Association between Eating Patterns and Obesity in a Free-living US Adult Population. *American Journal of Epidemiology* **158**, 85-92.
33. Wirt A, Collins CE (2009) Diet quality – what is it and does it matter? *Public Health Nutr* **12**, 2473-2492.
34. USDA (2014) A Series of Systematic Reviews on the Relationship Between Dietary Patterns and Health Outcomes.
35. Gao SK, Beresford SAA, Frank LL *et al.* (2008) Modifications to the Healthy Eating Index and its ability to predict obesity: the Multi-Ethnic Study of Atherosclerosis. *The American Journal of Clinical Nutrition* **88**, 64-69.
36. Jacobs DR, Sluik D, Rokling-Andersen MH *et al.* (2009) Association of 1-y changes in diet pattern with cardiovascular disease risk factors and adipokines: results from the 1-y randomized Oslo Diet and Exercise Study. *The American Journal of Clinical Nutrition* **89**, 509-517.
37. Cheng G, Gerlach S, Libuda L *et al.* (2010) Diet Quality in Childhood Is Prospectively Associated with the Timing of Puberty but Not with Body Composition at Puberty Onset. *The Journal of Nutrition* **140**, 95-102.
38. Park S-Y, Murphy SP, Wilkens LR *et al.* (2005) Dietary Patterns Using the Food Guide Pyramid Groups Are Associated with Sociodemographic and Lifestyle Factors: The Multiethnic Cohort Study. *The Journal of Nutrition* **135**, 843-849.
39. Di Cesare M, Khang Y-H, Asaria P *et al.* Inequalities in non-communicable diseases and effective responses. *The Lancet* **381**, 585-597.
40. Celis-Morales C, Lara J, Mathers JC (2014) Personalising nutritional guidance for more effective behaviour change. *Proc Nutr Soc* **FirstView**, 1-9.

41. Ferguson L (editor) (2013) *Nutrigenomics and Nutrigenetics in Functional Foods and Personalized Nutrition.* Florida: CRC Press.
42. Pursey K, Burrows LT, Stanwell P *et al.* (2014) How Accurate is Web-Based Self-Reported Height, Weight, and Body Mass Index in Young Adults? *J Med Internet Res* **16**, e4.
43. Macdiarmid J, Blundell J (1998) Assessing dietary intake: Who, what and why of under-reporting. *Nutr Res Rev* **11**, 231-253.

## 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, % | | | | | | | | | |
| Caucasian | 95.6 | | 96.5 | | 97.7 | | 98.1 | | 0.16 |
| Occupation, % | | | | | | | | | |
| Professional and managerial | 44.2[4] | | 37.8 | | 39.4 | | 32.2 | | **0.014** |
| Intermediate occupations | 25.9 | | 22.4 | | 28.5 | | 28.7 | | 0.16 |
| Routine and manual | 7.4[4] | | 6.8 | | 12.9 | | 14.3 | | **0.006** |
| Student | 13.5 | | 21.7 | | 9.5 | | 14.7 | | 0.18 |
| Not currently working | 9.1 | | 11.3 | | 9.8 | | 10.1 | | 0.38 |
| 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.

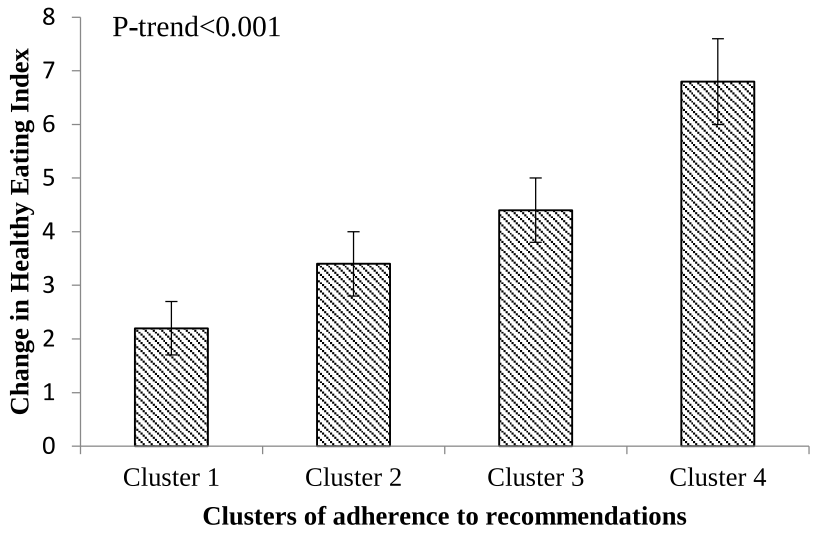
P-trend<0.001
Change in Healthy Eating Index
0
1
2
3
4
5
6
7
8
Cluster 1
Cluster 2
Cluster 3
Cluster 4
Clusters of adherence to recommendations

**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)

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)

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 ≥38g/day; >50yrs ≥30g/day) and females (18-50yrs ≥25g/day; >50yrs ≥21g/day); salt: 18-50yrs ≤3.75g/day; 51-70yrs ≤3.25g/day; >70yrs ≤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).

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)