REVIEW

Does Personalized Nutrition Advice Improve Dietary Intake in Healthy Adults? A Systematic Review of Randomized Controlled Trials

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ABSTRACT

Personalized nutrition (PN) behavior-change interventions are being used increasingly in attempts to improve dietary intake; however, the impact of PN advice on improvements in dietary intake has not been reviewed systematically. The aim of this systematic review was to evaluate the effect of PN advice on changes in dietary intake compared with generalized advice in healthy adults. Three databases (EMBASE, PubMed, and CINAHL) were searched between 2009 and 2020 for randomized controlled trials (RCTs) that tested the effect of PN and tailored advice based on diet, phenotype, or genetic information. The Evidence Analysis Library Quality Criteria checklist was used to conduct a risk-of-bias assessment. Information on intervention design and changes in nutrients, foods, and dietary patterns was extracted from the 11 studies meeting the inclusion criteria. Studies were conducted in the United States, Canada, or Europe; reported outcomes on 57 to 1488 participants; and varied in follow-up duration from 1 to 12 mo. Five studies incorporated behavior-change techniques. The risk of bias for included studies was low. Overall, the available evidence suggests that dietary intake is improved to a greater extent in participants randomly assigned to receive PN advice compared with generalized dietary advice. Additional well-designed PN RCTs are needed that incorporate behavior-change techniques, a broader range of dietary outcomes, and comparisons between personalization based on dietary, biological, and/or lifestyle information. *Adv Nutr* 2020;00:1–13.

Keywords: personalized nutrition, behavior change, systematic review, diet, dietary patterns, nutrition, adults, genotype, phenotype

Introduction

With poor diet now considered a top risk factor for noncommunicable diseases (1), improving dietary intake is a global priority (2, 3). Current public health campaigns using "one-size-fits-all" dietary recommendations are not achieving the changes in dietary behavior needed to shift dietary intake towards healthier dietary patterns (4, 5). Given the complex and varied nature of individual characteristics influencing dietary behavior, targeted, or personalized, dietary interventions based on these characteristics may be more effective than generalized advice (6, 7). With increasing agreement regarding the definition of personalized nutrition (PN) (6, 8), this review considers PN as an approach in which individual dietary intake, phenotypic information (e.g., anthropometric measurements and biomarkers of disease risk), and genetic information [e.g., single nucleotide polymorphisms (SNPs)] are used to design tailored nutrition advice (9, 10).

Few interventions have evaluated the effect of PN advice based on dietary, phenotypic, and/or genetic characteristics on improvements in dietary intakes and eating behaviors (9). Much research to date has focused on the effect of genetic-based PN advice on improvements in diet, with mixed results (11). While two 12-mo randomized controlled trials (RCTs) in Canadian adults have shown improvements in intakes of some nutrients (sodium and total fat) following the provision of advice based on carriage of specific risk variants (12, 13), trials in Europe that have studied changes in nutrients, foods, and/or overall dietary patterns have observed mixed results

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Abbreviations used: CVD, cardiovascular disease; FFQ, food-frequency questionnaire; PN, personalized nutrition; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; RCT, randomized controlled trial; SNP, single nucleotide polymorphism; T2D, type 2 diabetes.

for sustained and clinically relevant improvements in diet following the provision of genotype-based advice (9, 14, 15). Nevertheless, a recent systematic review of genetic testing and lifestyle behavior changes concluded that, of all lifestyle behaviors, changes in dietary intake were the most promising given that genetic testing led to practical recommendations that often focused on changes in diet (16). Few studies have examined the effect of personalized advice based on phenotypic characteristics and results have been mixed (9, 17) To date, the pan-European Food4Me study has been the only RCT to evaluate whether PN advice based on diet, phenotype, and genotype was more effective for improving nutrient, food-group intakes, and overall dietary patterns compared with generalized dietary advice (9).

Despite a rapid increase in commercial, direct-to-consumer PN testing and a systematic review on genetic testing interventions (18), there has been no systematic review of the evidence from studies that have tested the utility of PN based on current diet, individual biological characteristics, lifestyle information, and/or other personal attributes for improving dietary intake. Such a review is needed to provide a comprehensive and objective analysis of the outcomes of all PN interventions conducted to date. Moreover, there is a need to determine whether PN interventions improve dietary intake to a greater extent than conventional, generic, dietary advice when considering intakes of nutrients, food groups, and overall dietary patterns. This systematic review aimed to examine whether PN interventions produce bigger improvements in dietary intake than conventional dietary advice by qualitatively reviewing evidence from PN interventions in healthy adult populations. The results of this review will inform the design of future PN interventions and their potential for implementation into healthy eating strategies and direct-to-consumer PN offerings.

Methods

This systematic review was conducted according to the Cochrane Handbook for Systematic Reviews of Interventions (19) and reported using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (**Supplemental Table 1**) (20). The protocol was registered with PROSPERO, the International Prospective Register of Systematic Reviews (registration number CRD42019132050).

Search strategy

Electronic searches were conducted to identify studies reporting changes in dietary intakes (nutrients, foods, and dietary patterns) following a PN intervention. The following databases were searched systematically from July 2009 to June 2020: EMBASE, PubMed, and CINAHL. The search strategy combined 4 search themes using the Boolean operator "AND". The first theme was ("personalized nutrition" OR "personalised nutrition" OR precision OR genomics OR gene OR genes OR genetic OR genetics OR phenotype OR genotype OR DNA); the second theme was (nutrition OR diet OR diets OR dietary); the third theme was (change* OR effect* OR impact* OR modif*); and the fourth theme was (information OR recommendation OR advice OR intervention* or program* OR counsel*). The specific search strategies for EMBASE, PubMed, and CINAHL are presented in **Supplemental Table 2**. Reference lists of related publications and systematic reviews were hand-searched to identify other studies potentially eligible for inclusion.

Study selection and screening

Articles were included if they *1*) were randomized interventions; *2*) assessed the impact of personalized advice on change in nutrients, food groups, and/or dietary patterns; and *3*) were in healthy adults. Multicomponent interventions were included if dietary intake was included as an outcome. For the purpose of screening, personalized advice was defined as dietary advice based on either current dietary intake, genotype, and/or phenotype. Healthy adults were defined as individuals aged ≥18 y and without a chronic condition [e.g., self-reported or doctor diagnosed type 2 diabetes (T2D), cardiovascular disease (CVD), or cancer]. Therefore, studies were excluded if they specifically recruited individuals with a chronic condition. Studies that specifically recruited individuals with overweight or obesity were included in the present review due to the high proportion of individuals with overweight or obesity among the apparently healthy populations in the countries where the PN RCTs were carried out. However, individuals who are overweight or obese could have undiagnosed health problems and may enter a weight-loss intervention with very different motivators for behavior change. Thus, we reviewed these studies separately. Articles were excluded if they *1*) did not report dietary intake at both baseline and follow-up, *2*) were not in English, *3*) were observational or animal studies, or *4*) did not include a comparator group (i.e., nonpersonalized advice that was either generalized dietary or behavioral advice depending on the nature of the trial). Included studies were restricted to those published since 2009. This search period was selected on the basis that research on PN was very limited prior to 2009. A 2010 Cochrane review on the effects of communicating DNA-based disease-risk estimates on risk-reducing behaviors was hand-searched to confirm that no studies were missed (21). Multiple publications from the Food4Me study were identified in the search (9, 14, 22), and publications reporting changes in dietary intake in response to PN advice were included in this review (9, 14). Screening of titles and abstracts was performed using the selection criteria by independent reviewers (BM, AN, and RJ). Full texts of eligible articles were then assessed in duplicate (RJ and AN) and any discrepancies were resolved by consensus.

Data extraction and quality assessment

A data-extraction template was developed and piloted for use in this review. Two reviewers (BM and RJ) extracted the data independently, which were checked by a third reviewer (AN). Data were extracted on participants (age, sex, country), study design (intervention and control groups, follow-up duration,

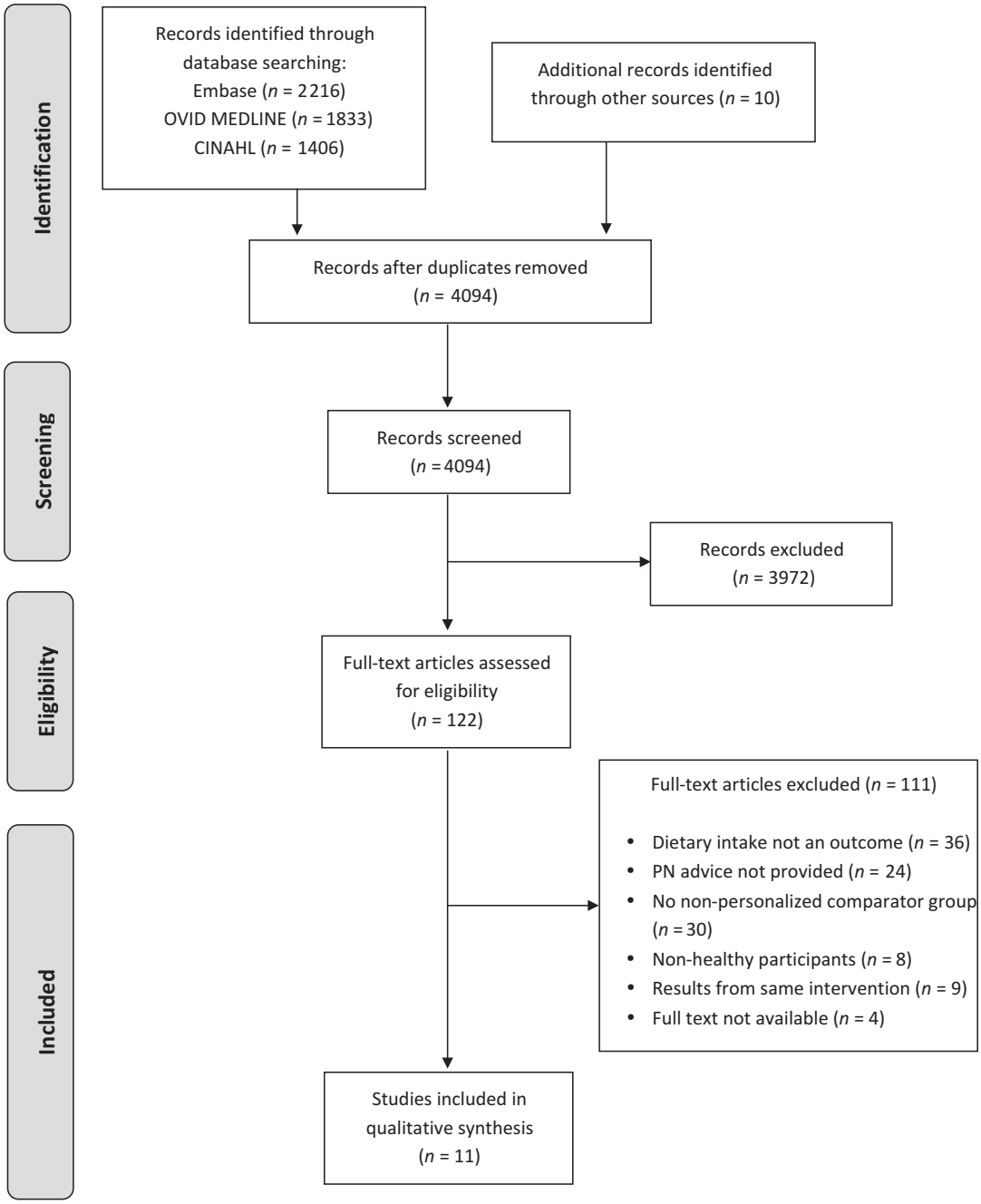

FIGURE 1 PRISMA flow diagram of included studies. PN, personalized nutrition; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

and dietary assessment methodology), intervention strategy (i.e., basis of PN advice), and outcomes (i.e., dietary intake or other outcomes assessed if a multicomponent intervention was used), results, and conclusions. The Academy of Nutrition and Dietetics Evidence Analysis Library Quality Criteria Checklist was used to conduct a risk-of-bias assessment on the studies that met the inclusion criteria (23). Two reviewers (BM and RJ) assessed studies independently and any discrepancies were resolved by consensus. An overall score (positive, neutral, negative) was assigned to each article based on 4 relevance questions and 10 validity questions (**Supplemental Table 3** and **Supplemental References**) (23).

Results

As detailed in **Figure 1**, our initial search identified 5465 articles. After removal of duplicates, 3972 were excluded based on their title and abstract and 122 full-text articles were reviewed. Eleven studies met the predetermined inclusion criteria for the systematic review. Studies were excluded for the following reasons: change in dietary intake was not an

intervention outcome ($n = 36$), no PN advice was provided ($n = 24$), no nonpersonalized comparator group ($n = 30$), participants were not free from chronic conditions as they had irritable bowel syndrome ($n = 2$), T2D ($n = 3$), coronary artery disease ($n = 1$) or cancer ($n = 2$), multiple publications from the same intervention study ($n = 9$), or full text not available ($n = 4$). No studies from the 2010 Cochrane review on the effects of communicating DNA-based disease risk estimates on risk-reducing behaviors met the eligibility criteria due to none providing PN advice ($n = 7$).

Of the 11 studies included, the sample size of participants varied from 57 (11) to 1488 (9), with an age range from 18 to 79 y; and all but 1 study (11) included both male and female participants (**Table 1**). Three were conducted in the United States (17, 24, 25), 3 were in Canada (11–13), and 5 were in Europe (9, 14, 15, 26, 27). The duration of follow-up ranged from ≤3 mo (11, 24, 26, 27), 6 mo (9, 14, 17, 25), to 12 mo (12, 13, 15). Five studies provided dietary advice based on genotype alone (11, 12, 15, 24, 25), 1 study provided dietary advice based on current diet only (27), and 4 studies provided advice based on a combination of current diet, phenotype, and/or genotype (9, 14, 17, 26). Comparator groups included generalized dietary advice based on a number of nutrients and/or foods (9, 12–15, 17, 24) or generalized dietary and lifestyle advice (11, 25–27). Five studies provided genotype-based advice related to disease risk (15, 17, 24–26), whereas 5 provided genotype-based advice related to metabolism (9, 11–14). Two studies were weight-management interventions that specifically recruited participants with a BMI (in kg/m^2) >25 (13, 27).

Five studies incorporated behavior-change techniques into their study design. Celis-Morales et al. (9) and Livingstone et al. (22) included a total of 17 behavior-change techniques to support sustained changes in dietary intake in the Food4Me Study, while Sparks et al. (17) used motivational interviewing techniques in one-on-one education for the intervention group. The 2 weight-management interventions included techniques based on either the theory of planned behavior or a combination of motivational interviewing, action, and coping plans and implementation intentions (13, 27). Conversely, the remaining studies did not report any specific behavior-change techniques. One study reported the use of theory-based models but did not specify which theory was used to inform the intervention (24).

Six studies focused on dietary intake as a primary outcome (9, 11, 12, 14, 15, 24). As shown in **Table 2**, dietary intake was measured using diverse instruments including 24-h dietary recalls, food-frequency questionnaires (FFQs), and brief dietary questionnaires. Foods and/or nutrients were measured as dietary outcomes in all included studies, whereas an overall dietary pattern (2010 Healthy Eating Index and Mediterranean Diet Score) was measured in 2 studies only (9, 14). The most commonly reported dietary outcome was change in fruit and vegetable intake.

Outcomes from the quality appraisal of included studies are shown in Supplemental Table 3 and Supplemental References. All studies received a "positive" overall rating, indicating that inclusion and exclusion criteria were defined, bias was low, and that data collection and data analysis procedures were appropriate (20).

As shown in Table 1, 8 of the 11 studies reported improvements in dietary intake following PN advice compared with the control group. These improvements were observed in ≥1 dietary outcome for at least 1 time point. Two Food4Me studies demonstrated that personalized advice (based on current diet, phenotype, and genotype) improved overall dietary patterns at 6 mo, as well as the intake of total energy, red meat, salt, saturated fat, and folate (9, 14). However, only one of these studies indicated that genotypic information may enhance the effectiveness of the PN advice above that achieved by PN based on analysis of current diet and phenotype.

The studies that investigated the effects of PN using genotype- or/and phenotype-based estimates of chronic disease risk and based on nutrient metabolism showed mixed results. Hendershot et al. (24) reported reduced alcohol intake following genotype-based advice on alcohol-related cancer risks. Additionally, Sparks et al. (17) tested the effectiveness of education on personalized rheumatoid arthritis risks based on a combination of genotype, phenotype, and behavioral factors, and observed increased intakes of fish and fruit. In contrast, 1 study that communicated genetic-based T2D risks did not demonstrate any effect on dietary intake (26). Similarly, while Kullo et al. (25) showed no additional effect of providing a CVD genetic risk score on dietary fat intake, Hietaranta-Luoma et al. (15) observed improved fat quality at 6 mo following advice based on CVD genetic risk but this improvement was not sustained at 12 mo. Roke et al. (11) found no effect of communicating a fat metabolism–related genotype, whereas Nielsen and El-Sohemy (12) showed a reduction in sodium intake at 12 mo in individuals who were informed that they had a genotype (risk version of the angiotensin converting enzyme gene) linked to higher sodium sensitivity. Moreover, Horne et al. (13) demonstrated that nutrigenomics-based macronutrient recommendation(s) to enhance weight loss reduced dietary fat intake more than the standard advice.

Discussion

This systematic review aimed to evaluate the effect of personalized interventions on changes in dietary intake. We observed some evidence for improvements in dietary intake in participants randomly assigned to receive PN advice compared with the control group. Given the clinical heterogeneity in the RCTs, future PN interventions of comparable designs are needed to facilitate meta-analysis of change in dietary intake. Additional recommendations for PN interventions include incorporating appropriate behavior-change techniques, including comparisons between different bases of personalization and standardizing reporting of dietary outcomes.

Although all studies in this review included genetic information as 1 element of the basis for personalized advice, there was little evidence that genotypic information was

TABLE 1 Characteristics of included studies[1]

Study, year (reference)	Participants (*n* baseline); age; country; and BMI (if applicable)	Study design, follow-up	Outcomes measured	Intervention group(s) conditions	Comparison group(s) conditions	Dietary results	Authors' conclusions
Celis-Morales et al., 2016 (9)	1488 (618 M/870 F); 18–79 y; Ireland, Spain, Poland, Netherlands, UK, Greece, Germany	RCT, 6 mo	Dietary intake,[2] anthropometrics, and biomarkers	L1: Dietary advice based on current diet; L2: Dietary advice based on current diet and phenotype (anthropometry, blood markers); L3: Dietary advice based on current diet, phenotype, and genotype (*FTO*, *FADS1*, *TCF7L2*, *ApoE*, and *MTHFR*). Advice designed using 17 BCTs	Dietary advice based on generalized dietary guidelines	Greater improvement in dietary pattern (2010 Healthy Eating Index), intake of energy, red meat, salt, saturated fat, and folate in participants who received personalized advice (L1+L2+L3) compared with the control at 6 mo	PN was more effective at improving dietary intake than population-based guidelines. No evidence that using phenotype and/or genotype increased effectiveness compared with advice based on current diet alone
Godino et al., 2016 (26)	569 (268 M/301 F); 39–55 y; England	RCT, 2 mo	Physical activity,[2] dietary intake, weight, health-related behavior, and attitudes	Phenotypic-based T2D risk (Cambridge Diabetes Risk Score based on age, sex, smoking status, family history of diabetes, prescription of steroid or antihypertensive medication) or genotype-based T2D risk (23 diabetes susceptibility SNPs)	No provision of phenotype or genotype	No effect of communicating genetic or phenotypic estimates of T2D on fruit and vegetable consumption	Communication of T2D risk estimates based on genotype or phenotype did not result in changes in dietary intake
Hendershot et al., 2010 (24)	200 (93 M/107 F); 19–22 y; USA	RCT, 1 mo	Alcohol consumption, risk perception, motivation, and behavioral intention	Genotype-based risk for alcohol-related cancer and alcohol dependence (*ALDH2*)	Non–genotype-based feedback relating to normal college student behaviors	Greater reduction in peak alcohol intake, typical weekend alcohol intake, and alcohol intake frequency among the high-risk	This study provides initial evidence for the feasibility of genetic risk estimates in alcohol-related health interventions

(*Continued*)

TABLE 1 (*Continued*)

Study, year (reference)	Participants (*n* baseline); age; country; and BMI (if applicable)	Study design, follow-up	Outcomes measured	Intervention group(s) conditions	Comparison group(s) conditions	Dietary results	Authors' conclusions
						alcohol-related cancer intervention group compared with the control group	
Hietaranta-Luoma et al., 2014 (15)	107 (33 M/74 F)[3]; 20–67 y; Finland	RCT, 12 mo	Dietary intake, alcohol consumption, physical activity, health, and taste attitudes	Genotype-based risk for CVD (*ApoE*)	General health information on lifestyle and CVD risk	Improvement in fat quality in high-risk genetic group compared with control at 6 mo. NS difference between groups at 12 mo for fruit and vegetables; decrease in high-fat/high-sugar food intake in low-risk genetic group compared with control at 12 mo	Personalized genetic information may affect fat quality within the diet, but more research is required to determine how to use genotype-based health information and achieve long-term changes
Kullo et al., 2016 (25)	203 (97 M/106 F)[3]; 45–65 y; USA	RCT, 6 mo	LDL-C,[2] dietary intake, physical activity, and anxiety	Genetic risk score (28 CAD-susceptibility SNPs) for 10-y probability of CAD	Nongenetic risk score for 10-y probability of CAD	No effect of communicating a genetic risk score of CAD on total fat intake compared with a conventional risk score alone	Providing genetic-based CAD risk estimates resulted in decreases in LDL-C concentrations compared with conventional CAD risk estimates. No effect on dietary fat intake
Livingstone et al., 2016 (14)	1480 (614 M/866 F); 18–79 y; Ireland, Spain, Poland, Netherlands, UK, Greece, Germany	RCT, 6 mo	Dietary intake	L1: Dietary advice based on current diet; L2: Dietary advice based on current diet and phenotype (anthropometry, blood markers); L3: Dietary advice based on current	Dietary advice based on generalized dietary guidelines	Greater improvement in Mediterranean Diet Score in participants who received personalized advice (L1+L2+L3) compared with control at 6 mo. Also, greater	After the intervention, Mediterranean Diet Scores were greater in individuals randomly assigned to receive PN than in controls, with the addition of DNA-based dietary

(*Continued*)

TABLE 1 (*Continued*)

Study, year (reference)	Participants (*n* baseline); age; country; and BMI (if applicable)	Study design, follow-up	Outcomes measured	Intervention group(s) conditions	Comparison group(s) conditions	Dietary results	Authors' conclusions
				diet, phenotype, and genotype (*FTO*, *FADS1*, *TCF7L2*, *ApoE*, and *MTHFR*). Advice designed using 17 BCTs		improvement in participants who received L3 dietary advice compared with L2 at month 6	advice resulting in the largest differences
Nielsen and El-Sohemy, 2014 (12)	138 (32 M/106 F); 23–35 y; Canada	RCT, 12 mo	Dietary intake	Genotype-based advice for caffeine, vitamin C, added sugars and sodium (*CYP1A2*, *GSTM2* + *GSTT1*, *TAS1R2*, *ACE*). Gave advice on specific dietary components and examined whether participants adhered to them	Generalized dietary advice for caffeine, vitamin C, added sugars, and sodium	Greater reduction in sodium intake among the high-risk intervention group compared with the control group at 12 mo; NS difference in caffeine, vitamin C, added sugar intake between the high-risk intervention group and control group at 12 mo	DNA-based dietary advice was shown to impact dietary intake to a greater extent than general population-based recommendations
Roke et al., 2017 (11)	57 (57 F); 18–25 y; Canada	RCT, 3 mo	Dietary intake,[2] biomarkers, and anthropometrics	Genotype-based advice (*FADS1*)	No genotype-based advice	No effect of communicating a genotype (*FADS1*) on EPA and DHA intake	The provision of personal FADS1 genetic information did not significantly change intake of dietary omega-3 FAs compared with the nongenetic group
Sparks et al., 2018 (17)	238 (56 M/182 F); 28–70 y; USA	RCT, 6 mo	Motivation,[2] dietary intake, dental, physical activity, and smoking	PRE-RA arm: genotype (*HLA-DRB1*) and phenotype (autoantibody *RF*/*CCP*) based personalized RA risk; PRE-RA Plus arm: PRE-RA arm +	Standard education about RA epidemiology, symptoms, and diagnosis	Participants in the PRE-RA arm and the PRE-RA Plus arm reported increased fish intake compared with participants in the control group at 6 mo;	The provision of personalized genotype- and phenotype-based RA and a corresponding education increased motivation to

(*Continued*)

TABLE 1 (*Continued*)

Study, year (reference)	Participants (*n* baseline); age; country; and BMI (if applicable)	Study design, follow-up	Outcomes measured	Intervention group(s) conditions	Comparison group(s) conditions	Dietary results	Authors' conclusions
				1-on-1 education. Advice designed using motivational interviewing BCTs		participants in the PRE-RA Plus arm reported increased fruits intake compared to participants in the control group at 6 mo	improve RA risk-related behaviors
Weight-management interventions							
Horne et al., 2020 (13)	140 (18 M/122 F); control: 56.4 (SD 12.1) y; intervention: 53.5 (SD 13.6) y; Canada; BMI ≥25 kg/m^2	RCT, 12 mo	Dietary intake and dietary adherence	Genotype-based advice: *UCP1* (rs1800592), *FTO* (rs9939609), *TCF7L2* (rs7903146), *APOA2* (rs5082), *PPARγ 2* (rs1801282), and *MC4R* (rs17782313). Participants were advised to focus on the macronutrient recommendation(s) that was/were highlighted in their genetic report to enhance weight-loss response. Advice designed using theory of planned behavior BCT	A calorie-controlled, moderately low-fat (25% kcal) nutrition plan	Participants in the intervention arm reported lower total fat intake (%E) compared with the control at 12 mo; NS changes in calories or %E from protein, SFA, or unsaturated fat . Participants in the intervention arm had greater adherence to recommendation for total fat, SFA, and protein intake compared with participants in the control group at 12 mo; NS differences in adherence for calories	A nutrigenomics weight-management intervention can motivate greater long-term dietary change compared with population-based recommendations
Anderson et al., 2018 (27)	78 (9 M/69 F); 18–72 y; Scotland; BMI ≥25 kg/m^2	RCT, 3 mo	Feasibility,[2] weight, physical activity, dietary intake, and psychosocial measures	A personalized diet based on current diet (600-kcal deficit dietary intake as recommended by	Usual care–lifestyle booklet	Participants in the intervention arm reported lower total fat intake compared with participants in the	The intervention had a favorable effect on fat intake score. Further work is needed to refine intervention

(*Continued*)

TABLE 1 (*Continued*)

Study, year (reference)	Participants (n baseline); age; country; and BMI (if applicable)	Study design, follow-up	Outcomes measured	Intervention group(s) conditions	Comparison group(s) conditions	Dietary results	Authors' conclusions
				the Scottish Intercollegiate Guidelines Network). Advice designed using motivational interviewing, action, and coping plans and implementation intentions BCTs		control group at 3 mo; NS changes in unsaturated fat or fiber intake	components, particularly dietary aspects that may need tailoring for ethnic groups

[1] $n = 11$. *ACE*, angiotensin I converting enzyme, *APOA2*, apolipoprotein type 2; *ApoE*, apolipoprotein E; BCT, behavioral change technique; CAD, coronary artery disease; CVD, cardiovascular disease; *CYP1A2*, cytochrome P450 family 1 subfamily A member 2; E, energy; FA, fatty acid; *FADS1*, fatty acid desaturase 1; *FTO*, fat-mass and obesity-associated; *GSTM2* + *GSTT1*, glutathione S-transferase mu 2 + glutathione S-transferase theta 1; *HLA-DRB1*, major histocompatibility complex, class II, DR beta 1; L1, Level 1 dietary advice based on current diet; L2, Level 2 dietary advice based on current diet and phenotype (anthropometry, blood markers); L3, Level 3 dietary advice based on current diet, phenotype, and genotype; LDL-C, LDL cholesterol; *MC4R*, melanocortin-4-receptor gene; *MTHFR*, 5,10-methylenetetrahydrofolate reductase; PN, personalized nutrition; *PPARγ2*, peroxisome proliferator-activated receptor gamma; PRE, personalized risk estimator; RA, rheumatoid arthritis; *RFYCCP*, rheumatoid factor and cyclic citrullinated peptides; RCT, randomized controlled trial; SNP, single nucleotide polymorphism; *TAS1R2*, taste receptor type 1 member 2; *TCF7L2*, transcription factor 7 like 2; T2D, type 2 diabetes; *UCP1*, uncoupling Protein 1.

[2] Indicates the primary outcome as identified in the publication. Absence indicates that no primary outcome was specified in the publication.

[3] Numbers are for follow-ups due to lack of baseline data.

effective in improving dietary intake. This is consistent with recent meta-analyses on the effect of genetic advice (16, 28, 29). Hollands et al. (28) concluded that communicating genetic-based risk had little or no impact in reducing health risk behaviors, while Li et al. (29) found no evidence that communication of genetic-based risk improved dietary or exercise behaviors of participants. In contrast, although Horne et al. (16) found that the genetic-based interventions provided to participants were overall of "poor" quality, they indicated that the evidence for lifestyle behavior change was most promising for genetic testing to improve dietary intake. The authors speculated that this was due to most genetic testing leading to recommendations for changing diet, rather than other lifestyle behaviors. However, findings from the present review found limited evidence to support benefits of genotype-based advice on changes in dietary intake as superior or more effective than other forms of personalization. Future RCTs are needed to test the effect of PN advice based on genotyping compared with PN advice derived on other individual participant characteristic(s). Moreover, research on genotype-based advice has been based on both single genotypes and on genetic risk scores that combine multiple SNPs of interest. To date, it is not clear which is the better approach. Use of single genotypes has the advantage that there may be evidence of specific diet–gene interactions that can provide objective guidance on dietary advice (30). Conversely, given that multiple genetic variants influence the risk of chronic diseases, the use of genetic risk scores will capture more of the genetic predisposition to disease at the cost of less certainty about what dietary changes are most appropriate.

Evidence suggests that phenotypic characteristics, such as drivers of taste preferences and metabolomics, might be beneficial to include in the design of PN advice (31). Recent research in a UK cohort of 1002 twins has advanced understanding of interindividual variability in postprandial response to food intake using machine learning approaches (7), supporting the need to leverage different features of human variability in the design of PN advice. Moreover, it will be important to address the psychological, social, economic, and cultural factors that influence eating patterns and that differ considerably between individuals (32, 33). In particular, there is a need to better understand the role of behavioral influences on the design and update of PN advice.

We propose that a key factor influencing the success of the PN interventions was the use of theory to underpin the intervention, consistent with the broader behavior-change literature (34, 35). Five studies within our review incorporated behavior-change theories into their study design, which may have contributed to the observed improvements in dietary intakes following the intervention. A recent systematic review of genetic-based trials by Horne et al. (16) found that lifestyle changes were more effective when studies implemented a model of behavior change. Of the studies that provided genotype-only advice, the 2 studies that showed large improvements in dietary intake were Nielsen and El Sohemy (12) and Hietaranta-Luoma et al. (15). Both

TABLE 2 Overview of dietary assessment methods and dietary outcomes used in the included studies[1]

Study, year (reference)	Dietary assessment method	Dietary outcome(s)
Horne et al., 2020 (13)	24-h dietary recalls (2 weekday and 1 weekend day)	Nutrients—energy (kcal/d), protein (%E/d and g/d), total fat (%E/d and g/d), saturated fat (%E/d and g/d), unsaturated fat (%E/d)
Celis-Morales et al., 2016 (9)	FFQ (157-item semi-quantitative)	Nutrients—energy (MJ/d), saturated fat (%E/d), polyunsaturated fat (%E/d), dietary fiber (g/d), salt (g/d), folate (μg/d) Food groups—fruits (g/d), vegetables (g/d), fruit and vegetables (g/d), whole grains (g/d), oily fish (g/d), red meat (g/d), low-fat dairy (g/d), salt (g/d) Dietary patterns—2010 Healthy Eating Index
Livingstone et al., 2016 (14)	FFQ (157-item semi-quantitative)	Dietary patterns— Mediterranean Diet Score
Godino et al., 2016 (26)	FFQ (130-item semi-quantitative)	Food groups—fruit and vegetables (g/d)
Nielsen and El-Sohemy, 2014 (12)	FFQ (196-item semi-quantitative)	Nutrients—sodium (mg/d), caffeine (mg/d), vitamin C (mg/d), added sugars (%E/d)
Roke et al., 2017 (11)	FFQ (37-item semi-quantitative)	Nutrients—EPA and DHA (mg/d)
Anderson et al., 2018 (27)	FFQ (19-item semi-quantitative) and 7-d alcohol record	Nutrients—fat score, unsaturated fat score, fiber score Food groups—alcohol (units/d)
Hietaranta-Luoma et al., 2014 (15)	Brief dietary questions (4 questions)	Nutrients—fat quality (scale, 0–27) Food groups—consumption of vegetables, fruits, and berries (portions/d), consumption of foods containing excessive fat and sugar (frequency/wk), alcohol consumption (frequency/mo or wk, portions/wk)
Sparks et al., 2018 (17)	Brief dietary questions (7 questions)	Food groups—fish, fruit, vegetables, and beans/nuts, fats/oils, meat/poultry, and sugars (frequency/wk)
Hendershot et al., 2010 (24)	Daily drinking questionnaire	Food groups—frequency of alcohol use (scale, 1–7), maximum drinks consumed, typical number of drinks on weekend nights
Kullo et al., 2016 (25)	Brief dietary questions (1 question)	Nutrients—total fat scale (0 = no fat intake to 110 = indicative of very high dietary fat intake)

[1] E, energy; FFQ, food-frequency questionnaire.

studies also had the longest duration of follow-up (12 mo) and so demonstrated sustained behavior change. Although neither study specified the use of particular behavior-change techniques, the success of one of these studies may be attributable to consideration of health behaviors. Hietaranta-Luoma et al. (15) designed health risk messages based on a 4-step model of response efficacy, self-efficacy, susceptibility, and severity. When designing future nutrigenomics-based PN interventions, researchers should ensure their studies are based on sound theories of behavior change known to motivate behavior change (36).

The demographics of participants included in the interventions differed between studies. While young adults may be more inclined to adopt change, they may be less likely to maintain it (34). Conversely, older adults may find it more difficult to adopt a new health behavior but may be more motivated to maintain the change (36, 37). It is well established that females are more likely to participate in nutrition-related research than males, partially explained by a greater interest in health and nutrition (38, 39). Moreover, findings from the Food4Me study suggest that males are less likely to be interested in, and to benefit from, a PN intervention (22, 40). Thus, given that all studies contained a higher proportion of female participants (range: 52–100%), the design of future PN interventions should consider accommodating motivators of behavior change specific to males. Participants in the Food4Me study were broadly representative of the European adult population with regard to their diet and lifestyle behaviors (40); however, similar to the majority of the studies within our review, most were participants with high levels of education or grade of employment. A large proportion of the customer base for direct-to-consumer genetic testing is highly educated and of high socioeconomic status (41). In general, population groups with lower socioeconomic status have poorer diets and experience a higher prevalence of obesity and chronic diseases (42, 43) and will thus experience different challenges in making dietary changes. Moreover, PN interventions are being increasingly targeted to the general population and will thus need to account for any changes in eating habits in everyday life as a result of influences from family, society, and socioeconomic conditions (43, 44). Of the 11 studies in the present review, only 3 were in nonwhite or mixed-ethnicity participants (11, 12, 24). Consequently, given differences in behavioral and biological characteristics between different ethnic groups (45), future studies should investigate the efficacy of PN nutrition approaches in different ethnic groups and explore the participant characteristics that are most appropriate for PN interventions in such groups (46).

Our review suggests that the design of the PN intervention may impact on the degree of dietary change observed. At

least for older people, evidence from dietary interventions suggests that changes seen at 6 mo are likely to be sustained for at least 12 mo (36). Moreover, the frequency of feedback has been shown to impact on dietary changes, where more frequent PN feedback amplified changes in dietary intake but also increased drop-out rates (47). The design of the dietary advice and subsequent analysis should also be considered. In 2 of the included studies (9, 12), not all participants received the same targeted dietary advice and so the investigators also ran analyses for each dietary outcome restricted to the participants who were provided with advice about that dietary outcome. These findings emphasize the scope for future research to explore the optimal features of PN intervention study design, while also incorporating existing best-practice behavior-change principles (6).

The studies included in this review measured a variety of dietary outcomes using either FFQs or brief diet questions. Some studies focused on specific nutrients, such as omega-3 fatty acids (11), alcohol (24), caffeine, vitamin C, added sugar, and sodium (12), while others included intake of nutrients, food groups (9, 16, 19, 20), and overall dietary patterns (9, 14). A broader range of dietary outcomes investigated would enable a more rigorous appraisal of changes in dietary intakes, including investigating whether intakes of specific nutrients, specific food groups, or entire dietary patterns are affected differentially following PN advice. While a focus on individual nutrients may offer insights into particular nutrient–disease relations in specialized population groups, foods and nutrients are not eaten in isolation, and dietary guidelines and policies internationally have an increasing focus on dietary patterns (5, 48, 49). Future research should thus consider the effect of PN advice on overall dietary patterns and eating occasions and should use appropriate dietary assessment tools to capture this additional information (50, 51). This information will be particularly important for understanding the feasibility of implementing PN advice based on dietary patterns, given that changing some dietary components (e.g., increasing vegetable intake) may be achieved more easily than others (e.g., reducing fat intake). In addition, achieving 1 goal at a time may be more successful than implementing multiple changes at once (52). However, from a population health perspective, improving the overall dietary pattern is likely to be the major goal.

This review has a number of strengths. It included a systematic review of a broad range of PN RCTs, providing qualitative insights into the benefit of PN approaches to improve dietary intake. In addition, we have investigated the features of effective PN interventions, thus informing the design of future PN interventions. A further strength of this study is the use of a clear definition of PN to inform the selection of included studies, which provided a framework for evaluating and comparing PN intervention designs. This study followed the PRISMA guidelines and included a risk-of-bias assessment, which showed that the majority of studies included were given a positive rating.

Our review has several limitations. First, the nature of PN interventions makes blinding challenging (53). Moreover, given that the studies included in this review utilized self-reported measures of dietary intake, results may be subject to recall and social desirability biases (50, 54). Detail on dietary intake was limited in most studies, given that brief dietary questions and FFQs were the most commonly used dietary assessment methodologies. Nonetheless, social desirability bias is expected to be less prevalent in the web-based interventions included in this review, given that perceived anonymity is higher (9, 17). Dietary change requires conscious cognitive effort by participants to make multiple choices daily that align with the prescribed changes. Compliance was not reported for some of the included studies (11, 12, 15, 17, 24, 25), and thus we recommend that future PN interventions report results according to the CONSORT guidelines (55). Last, the heterogeneity of PN RCTs conducted to date precludes meta-analysis.

In conclusion, the present review provides evidence that the provision of PN advice based on a combination of dietary information, phenotype, genotype, and/or lifestyle factors improved dietary intakes in healthy adult populations when compared with generalized dietary advice. These findings have implications for the design of future PN interventions aiming to improve healthy eating behaviors. More well-designed and executed RCTs are required to strengthen the evidence base for PN, so that, if appropriate, these strategies can be effectively incorporated into health care. To optimize public health benefit, research should examine PN interventions to improve overall dietary patterns as well as intakes of individual foods and nutrients. Moreover, future PN interventions should consider a wider range of individual characteristics that influence both food intake and the capacity to make, and sustain, dietary changes and should incorporate relevant behavior-change techniques.

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