Self-efficacy, habit strength, health locus of control and response to the personalised nutrition Food4Me intervention study

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AUTHOR CONTRIBUTIONS

The intervention study was designed by JM, and MG. Psychological constructs for analysis were selected by LF, BS-K, AR, RP and AF. CC-M and KL were involved in data collection and analysis. The plan for analysis was devised by BS-K, BB, RP, IL and JM. BS-K drafted the manuscript. LF, JM, CC-M, RP, AR, SK and AF commented on the draft manuscript.

CONFLICT OF INTEREST STATEMENT

The authors know of no conflict of interest that could impact upon the integrity of these results. The research funder was not involved in the study design; collection, management, analysis, and interpretation of data; writing of the report; or the decision to submit the report for publication. Materials and dataset are available from the corresponding author on request. All authors have approved the final submitted manuscript.

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ABSTRACT

Purpose: Randomised controlled trials identify causal links between variables but not why an outcome has occurred. This analysis sought to determine psychological factors assessed at baseline influenced response to personalised nutrition. Design: Web-based, randomised, controlled trial (RCT) was conducted across seven European countries. Volunteers, both male and female, aged over 18 years were randomised to either a non-personalised (control) or a personalised (treatment) dietary advice condition. Linear Mixed Model Analysis with fixed effects was used to compare associations between Internal and External Health Locus of Control (HLoC), Nutrition Self-Efficacy (NS-E) and Self-Report Habit Index (S-RHI) at baseline (N=1444), with Healthy Eating Index (HEI) and Mediterranean Diet Index (MDI) scores between conditions post-intervention (N=763). Findings: An increase in MDI scores was observed between baseline and six months in the treatment group which was associated with higher NS-E ($P<0.001$), S-RHI ($P<0.001$) and external HLoC ($P<0.001$). Increase in HEI between baseline and six months in the treatment group was associated with higher NS-E ($P<0.001$) and external HLoC ($P=0.009$). Interaction between time and condition indicated increased HEI scores ($P<0.001$) which were associated with higher S-RHI scores in the treatment than control group ($P=0.032$). Internal HLoC had no effect on MDI or HEI. Originality: Psychological factors associated with behaviour change need consideration when tailoring dietary advice. Those with weaker habit strength will require communication focussed upon establishing dietary habits and support in integrating advised changes into daily routine. Information on habit strength can also be used to inform how progress toward dietary goals are monitored and fed back to the individual. Those with stronger habit strength are more likely to benefit from personalised nutrition.

Key words: self-efficacy; health locus of control; habit strength; Healthy Eating Index; Mediterranean diet.

INTRODUCTION

Personalised nutrition uses information about an individual to deliver tailored dietary advice (Ordovas *et al.,* 2018) and could offer an effective way of motivating people to improve their diet-related behaviour and so to improve their health (Celis-Morales *et al.,* 2014). Randomised controlled trials (RCT), represent the gold-standard for inferring causality *i.e.* whether a particular condition or variable had an effect on an outcome when all other variables are held constant (Celis-Morales *et al.*, 2014). Previous studies have indicated that personalised advice is more effective than generic advice in producing healthy dietary change (Rollo *et al.,* 2020; Hoevaars *et al.,* 2020; Celis-Morales *et al.*, 2015). Even when the outcome of a dietary intervention is known, however, it is important to understand the psychological processes that may be involved in achieving the outcome so that future benefits can be maximised (Olsen, 2016). A key issue is inter-individual variability in response to interventions (Madden *et al.,* 2011). Understanding the psychology underlying inter-individual variability in response could prove valuable when designing future interventions. Individuals may respond differently to intervention depending upon their psychological propensity for behaviour change (Galekop *et al.*, 2021; Greiner *et al.*, 2018; Anderson *et al.,* 2000).

A review of digitally delivered healthy eating interventions (Olsen, 2016) concluded that approximately 75% of studies that provided feedback based upon behavioural theories resulted in short-term healthy change. A recent RCT (Rollo *et al.,* 2020), for example, has indicated that aspects of Social Cognitive Theory (SCT) such as self-monitoring and feedback may be particularly important to motivation. Qualitative research (Rankin *et al.,* 2016; Stewart-Knox et al., 2013) and survey of European consumers (Poínhos *et al.,* 2014), suggested that constructs associated with SCT such as nutrition self-efficacy (NS-E), health locus of control (HLoC) and habit strength (S-RHI) were potentially important factors determining intention to adopt personalised nutrition. While there has been much emphasis on behaviour change techniques, less attention has been paid to the impact of psychological variables upon intervention. These constructs were therefore included in the questionnaire administered to participants in this intervention trial rendering it one of few studies to have quantified markers of intention to change behaviour when assessing change in dietary outcomes (Carey *et al.,* 2018).

Habit refers to the non-cognitive (automatic), learned, component of behaviour (Gardner *et al.,* 2011). Past dietary habits are important to future intentions and food choices (Verhoeven *et al.,* 2012; de Bruijn, 2010). Habit strength assessed using the self-report habit index (S-RHI) (Honkanen *et al.,* 2005; Verplanken and Orbell, 2003) has been associated with intake of high energy snacks (Wouters et al., 2018; Naughton *et al.,* 2015), and with intention to consume soft drinks (Judah *et al.,* 2020; de Bruijn and van den Putte, 2009), fruit (van Keulen *et al.,* 2021; Bartle *et al.,* 2019; de Bruijn *et al.,* 2007; Brug *et al.,* 2006), meat (Rees *et al.,* 2018) and seafood (Honkanen *et al.,* 2005). Habit explains about 20% of nutrition behaviour (Gardner *et al.,* 2011). Interventions that target habit, therefore, could be effective in healthy dietary change (Gardner *et al.,* 2014). Habit strength for healthy eating measured using the S-RHI has been associated with long-term weight loss (Phelan *et al.,* 2020). Messages that target habit have been found to increase fruit and vegetable intake in students (Rompotis *et al.,* 2014). Personal plans that exclude less 'healthy' foods may prove difficult to adhere to as they require long-term modification of habitual dietary choices that have become automatic and beyond an individual's conscious control (Verhoeven *et al.,* 2012). Given that the main public health aim of personalised nutrition is to enable people to achieve a long-term, sustained healthy diet, Habit Strength could be important to consider in achieving sustained dietary behaviour change.

Locus of Control (LoC) refers to the extent to which a person believes that their actions can determine outcomes (Rotter, 1966). Health Locus of Control (HLoC) (Gebhardt *et al.,* 2001; Wallston *et al.,* 1978) is LoC that is associated with health behaviours (Lee *et al.,* 2019;

Cheng *et al.*, 2016; Ryon and Gleeson, 2014). HLoC is considered an important mediator of health behaviour change (Davey *et al.*, 2019; Jang and Baek, 2018; Marteau *et al.*, 2010). HLoC can be *internal*, reflecting the extent to which outcomes are perceived to be determined by the individual themselves, or *external*, the degree to which control is perceived to be determined by chance and/or other individuals (Ryon and Gleeson, 2014). where non-clinical, general populations have been studied, higher internal HLoC has been associated with healthier eating (Davey *et al.*, 2019; Rongen *et al.*, 2014; Cobb-Clark *et al.*, 2014; Murphy *et al.*, 2001; Paxton and Scunthorpe, 1999; Callaghan, 1998). Conversely, those who have a low internal HLoC consider their health to be less under their own control may be less likely to follow dietary advice (Marteau *et al.*, 2014; Frosch *et al.*, 2005). Previous research that has considered external HLoC has been mixed and while one study identified a link to healthier eating (Jang and Baek, 2018), other studies have found it to be associated with less healthy dietary habits (Gomez et al., 2018; Cheng *et al.*, 2016).

Self-efficacy refers to perceived ability to complete a specific task (Bandura, 1997), implying that behaviour change is most likely when self-efficacy is high (Witte and Allen, 2000). Consistent with this theory, cross-sectional studies in clinical populations (Greiner *et al.*, 2018; Gomez *et al.*, 2018; Hwang, 2016; Ferranti *et al.*, 2014) and apparently healthy populations (Lo *et al.*, 2019; Churchill *et al.*, 2019; Kushida *et al.*, 2017; Swan *et al.*, 2015; Williams *et al.*, 2012; Brug *et al.*, 2006; Anderson *et al.*, 2000) have linked higher self-efficacy to healthier food choices. Greater self-efficacy has been linked to more frequent fruit and vegetable intake (Smith *et al.*, 2020; Lo *et al.*, 2019; Welch and Ellis, 2018; Kushida *et al.*, 2017; Brug *et al.*, 2006), reduced fast food intake (Smith *et al.*, 2020) and less snacking (Churchill *et al.*, 2019). Conversely, lower self-efficacy has been associated less healthy food choices (Williams *et al.*, 2012; de Bruijn and van der Putte, 2009) and low perceived ability to cook healthy food (de Borba *et al.*, 2021). Evidence from recent RCT (Bouwman *et al.*, 2020) has indicated that higher self-efficacy can improve vegetable intake and adherence to healthy eating plans. Recent research (Bracken and Waite, 2020) and systematic review (Newby *et al.,* 2020) have implied that self-efficacy is associated with response to digitally-delivered behaviour change interventions. Together, this suggests that individuals with higher NS-E would be more likely to achieve healthy dietary behaviour changes following personalised nutrition advice.

Primary results from the Food4Me personalised nutrition intervention observed greater improvements in dietary quality in response to personalised nutrition than non-personalised dietary advice (Celis-Morales et al., 2017; Livingstone *et al.*, 2016a; Livingstone *et al.,* 2016a; Celis-Morales *et al.,* 2015). This analysis aims to determine the moderating effect that psychological factors associated with behaviour change have on response to personalised nutrition. Knowledge of these effects will allow the design of future interventions that are strengthened by the specific psychological construct levels individuals may have. By understanding what psychological factors contribute to an individual's response to personalised nutrition, we can then tailor advice that is optimally supported by understanding of their internal health locus of control, self-efficacy and/or habit strength. A secondary data analysis, therefore, has been conducted to investigate if baseline psychological traits contribute to the differences in response to personalised nutrition.

The purpose of this analysis, therefore, has been to determine the impact of Health Locus of Control (HLoC) (Internal and External), Nutrition Self-Efficacy (NS-E) and Habit Strength (S-RHI), at baseline upon dietary response to personalised versus non-personalised dietary advice. This was achieved by investigating associations between baseline psychological factors and HEI and MDI scores in response to non-personalised dietary advice (Level 0: Control) and differences in personalised nutrition advice (Levels 1 to 3 versus Treatment). Social cognitive theory (SCT) holds that self-efficacy and perceived control are interlinked

(Bandura, 1997) and as such, should be studied together (AbuSabha and Achterberg, 1997). According to SCT, individuals with low self-efficacy and high External HLoC will be less likely to alter dietary habits in response to dietary interventions (Joost *et al.*, 2007). It is predicted, therefore, that those higher in NS-E with higher Internal HLoC, lower External HLoC and higher habit strength (S-RHI) will be more likely to respond positively to personalised nutrition advice and that this will be reflected in higher HEI and MDI scores.

METHOD

Analysis was conducted on anonymised data collected as part of a web-based RCT (NCT01530139) conducted between August 2012 and December 2014 and which compared dietary response to personalised nutrition and Control (non-personalised) healthy eating advice. This study was conducted according to the guidelines laid down in the declaration of Helsinki and all procedures were approved by the Ethics committee of each recruiting centre: University College Dublin, Ireland; Maastricht University, Netherlands; University of Navarra, Spain; Harokopio University, Greece; University of Reading, UK; National Food and Nutrition Institute, Poland; and, Technische Universität München, Germany. All participants were informed of the study purpose and procedures prior to providing written consent.

Sampling

Details of recruitment, data collection procedures and intervention protocol have been reported previously.[51] Volunteers, both male and female, aged 18+ years were recruited to the 6-month online nutrition intervention study. Exclusion criteria were: pregnant or lactating; following a prescribed diet; having a metabolic condition which could alter their nutritional requirements; and, having no or limited internet access. Eligible volunteers (N=1607) were stratified by country (UK, Greece, Spain, Poland, Ireland, Germany and the Netherlands), sex and age before being equally allocated to one of three Treatment conditions using an urn randomisation scheme (Wei and Lachin 1988). Treatments were personalised advice based on: i) current diet assessed on healthy eating guidelines and anthropometry (n=414); ii) current diet and anthropometry plus phenotype (blood glucose, total serum cholesterol, carotenes and n-3 index) (n=404); iii) current diet and anthropometry plus phenotype plus genotype (specific variants of the following genes: *MTHFR, FTO, TCF7L2, APOE ε4* and *FADS1*) (n=402). The Control group (n=387) received non-personalised healthy eating advice based on European recommendations to reduce fat and salt intake and encouraging consumption of fish, fruit and vegetables (Control). The trial was single-blinded so that researchers did not know to which treatment participants were allocated. Psychological outcomes were available for 1507 cases at baseline, of whom 387 were in the control group and 1120 who underwent the personalised nutrition treatment. Of these, as a result of attrition, dietary outcomes were recorded for 763 post-intervention.

Measures

A questionnaire, the content of which was informed by prior qualitative research (Stewart-Knox *et al.,* 2013; Rankin *et al.,* 2016), was issued at baseline *via* an email link to assess health locus of control, nutrition self-efficacy and habit strength.

Health Locus of Control

Health locus of control (Gebhardt *et al.*, 2001) was measured by six items taken from the Revised Health Hardiness Inventory (RHHI-24) for which responses were on a 5-point Likert scale ranging from 1 = 'Completely disagree' to 5 = 'Completely agree'. The RHHI-24 comprises 4 scales: health as a value; perceived health confidence; IHLoC; and, EHLoC. Given the need to constrain the length of the questionnaire and the focus upon HLoC, the first three items of the IHLoC and EHLoC scales were extracted for inclusion. Items selected to measure IHLoC were: “I can be as healthy as I want to be”; “I am in control of my health”; “I can pretty much stay healthy by taking care of myself”; and “Efforts to improve your health are a waste of time” (which was reverse scored). Items used to measure HLoC were: “I am bored by all the attention that is paid to health and disease prevention”; “What's the use of concerning yourself about your health you'll only worry yourself to death”. As these items were negatively worded the 5-point Likert scales were reverse scored. Reliability was satisfactory with Cronbach’s α = 0.73 for IHLoC and α = 0.60 for EHLoC.

Nutrition Self-Efficacy

Nutrition self-efficacy (NS-E) was measured using Schwarzer and Renner’s (2000) Perceived Self-Efficacy Scale (PS-ES). The scale was adapted from a 4-point to a 5-point scale to align responses with others in the questionnaire. Respondents were asked how certain they were they could ‘manage to stick to healthy foods, even if’ on a scale ranging from 1 = ‘Very uncertain’ to 5 = ‘Very certain’, in response to the following items: “I need a long time to develop the necessary routines”; “I have to try several times until it works”; “I have to rethink my entire way of nutrition”; “I do not receive a great deal of support from others when making my first attempts”; “I have to make a detailed plan”. Reliability was good with Cronbach’s α = 0.87.

Habit Strength

Habit Strength was assessed using four items measuring each facet of habit (frequency; lack of awareness; lack of control; and, mental efficiency) previously employed by Honkanen and colleagues (2005) and adapted from Verplanken & Orbell’s (2003) Self-Report Habit Index (S-RHI). Responses were on a 5-point Likert scale ranging from 1 = ‘Completely disagree’ to 5 = ‘Completely agree’, to the following statements: “Eating healthily is something I do frequently”; “I eat healthily without having to consciously think about it”; “I feel weird if

I don't eat healthily"; "Eating healthily is something I do without having to think about it". Each item was scored and summed on four dimensions: frequency of behaviour; awareness; lack of control; and, mental efficiency. Reliability was satisfactory Cronbach's $\alpha = 0.73$.

Food Frequency Questionnaire

Procedures for computing Healthy Eating Index (HEI) and Mediterranean Diet Index (MDI) scores have been reported previously by Livingstone and colleagues (2016 a and b). Briefly, a validated 157-item food frequency questionnaire (FFQ) developed and validated for the study (Marshall *et al.*, 2016; Fallaize *et al.*, 2014; Forster *et al.*, 2014) was completed on-line at baseline and at six months. Responses were graded on 14 criteria to determine adherence to the Mediterranean diet (Livingsone *et al.*, 2016a; Martinez-Gonzalez *et al.*, 2012). Diet quality was also assessed using the healthy eating index (HEI) updated (2010) version (Guenther *et al.*, 2014). The HEI-2010 includes 12 food groups, 9 of which assess adequacy of the diet, including 1) total fruit; 2) whole fruit; 3) total vegetables; 4) greens and beans; 5) whole grains; 6) dairy; 7) total protein foods; 8) seafood and plant proteins; and 9) fatty acids. The remaining 3, refined grains, sodium, and empty calories (i.e., energy from solid fats, alcohol, and added sugars), assess dietary components that should be consumed in moderation. For all components, higher scores reflect better diet quality because the less beneficial food groups are scored such that lower intakes receive higher scores. The scores of the 12 components were summed to yield a total score with a maximum value of 100. The food groups of the HEI-2010 and their respective standards have been described in additional detail previously (Guenther *et al.*, 2014). For all components, higher scores reflect better diet quality because the less beneficial food groups are scored such that lower intakes receive higher scores. The HEI (2010) and MDI both show good validity (Guenther *et al.*, 2014) and changed in a positive direction in response to personalised nutrition advice (Celis-Morales *et al.*, 2017; San-Cristobal *et al.*, 2017).

Data Analysis

Linear Mixed Model with fixed effects, with the assumption of compound symmetry relating to the variances and covariance, was used to examine effect of psychological traits assessed at baseline on HEI and MDI scores between the Control and Treatment groups and time point (baseline and post-intervention) (Field, 2018). Dietary and psychological data for the three Levels of personalised nutrition were combined to make one treatment group. Separate models were run for the HEI and MDI, with the treatment and control conditions together within each model. Associations between psychological factors and dietary outcomes (HEI/MDI) are reported for a given intervention level (ie. simple effect) as a way of analysing conditional/interaction data when there is a mixed regression analysis. Baseline NS-E; IHLoC; EHLoC; and, S-RHI scores were entered into the analysis as independent variables. Outcome variables were HEI and MDI scores calculated for the Treatment (personalised nutrition) and Control (non-personalised advice) groups. Model results are presented as unstandardized estimates (est) and standard errors (s.e.). Where data were available for a given occasion this was retained, and where missing, the estimation method employed (maximum likelihood), estimated the parameter under the assumption that missing data were missing at random. All analyses were conducted using SPSS for Windows version 25.0. *P*-values < 0.05 were considered significant.

RESULTS

The eventual sample comprised those successfully followed-up at 6 months (N=763) and was predominantly (96.9%) white European, of whom 42% were male, with a mean age of 40 years (SD = 13) and a mean BMI of 25.4 kg/m^2 (SD = 4.8). Psychological traits appeared stable across the intervention period (Table 1). Those who completed the intervention were significantly higher in S-RHI than those who did not complete (Table 2). There were no differences between completers and non-completers in NS-E, IHLoC or EHLoC.

Insert table 1 and 2 here

Healthy Eating Index (HEI)

Main effects indicated that HEI scores increased between baseline and 6 months in the Treatment group (est=-2.54, se=0.39, $P<0.001$) and were positively associated with higher EHLoC, S-RHI and NS-E (Table 3). There was no significant association between IHLoC and HEI in either the Treatment or Control group and no significant association between EHLoC or NS-E and HEI in the Control group. The level-1 variance was 41.22 (se = 2.15) and the level-2 variance for the random intercept was 42.51 (se = 3.07).

Insert Table 3 here

Time and Condition

Taking the treatment condition from the second time-point (6 months) as the reference category, an interaction on time and condition was used. This can also be viewed as the comparison between those in the intervention conditions on the first occasion and its difference on the second occasion (est=-0.391). With this reference category a number of other potential interactions could be examined such as (a) those in the Control condition at baseline and (b) those in the Control condition on the follow-up occasion. Neither of these potential interactions were statistically significant. HEI scores were found to be significantly higher at 6 months than at baseline in the treatment group (est=-2.54, se=0.39, *P*<0.001) (Table 3).

Taking NS-E as the reference category, NS-E was not significant for those in the control group but had a statistically significant effect on HEI scores in the Treatment group (est=1.71, se=0.39, *P*<0.001). In other words, the effect of NS-E on HEI scores was different between conditions (ie. an interaction). This time X condition interaction, however, was not statistically significant (est=-0.65, se=0.75, *P*=0.387).

Taking EHLoC as the reference category, EHLoC also had a statistically significant effect on HEI scores in the Treatment condition (est=1.06, se=0.40, *P*=0.009). Again, the interaction between time and condition was not significant (est=-0.55, se=0.80, *P*=0.496). There was no effect of IHLoC on HEI scores (est=-0.02, se=0.35, *P*=0.671), nor was the interaction between time and condition significant (est=0.94, se=0.68, *P*=0.165).

Taking S-RHI as the reference category, S-RHI had a statistically significant effect on HEI scores in the Treatment condition (est=3.42, se=0.33, *P*<0.001). The interaction between time and condition was statistically significant and indicated that S-RHI had an effect on HEI and that scores were significantly higher in the Treatment group at 6 months (est=-1.44, se=0.67, *P*=0.032). In other words, in the Treatment group (personalised nutrition), the coefficient for the regression of baseline S-RHI on HEI at 6 months (having controlled for baseline HEI) indicated a positive association with HEI and a statistically significant effect (0.05 level) on response to intervention. Habit strength at baseline also had a greater effect on HEI scores post-intervention in the Treatment (personalised nutrition) than the Control (non-personalised) group.

There were no differences between the Control and Treatment groups in the association between NS-E, Internal HLoC or External (EHLoC) at baseline and HEI scores post-intervention.

Estimated Marginal Means (HEI)

The estimated marginal means (EMM) gave us the expected means conditioned on the model. At baseline, those in the Control condition had an EMM of 49.80 (SD = 9.51) that was marginally higher than the value obtained in the Treatment group at the baseline (49.50) (SD = 10.02). At six-months, the obtained value for the Treatment group was 52.04 (SD = 9.55), while the value was 51.26 (SD = 9.27) for the Controls.

Mediterranean Diet (MDI)

The Treatment group showed a time effect on MDI scores which increased between baseline and six months (est=-3.91, se=0.07, *P*<0.001). MDI scores were positively associated with EHLoC, S-RHI and NS-E in the Treatment group (Table 3). MDI scores were negatively associated with IHLoC and positively associated with S-RHI in the Control group. There was no significant association between MDI scores and IHLoC in the Treatment group or with EHLoC or NSE in the Control group. The level-1 variance was 1.36 se = 0.07 and the level-2 random intercept value was 1.24 se = 0.10.

Time and Condition

Using the Treatment condition from the second time point (6 months) as reference category an interaction between time and condition was employed. MDI scores were significantly higher at 6 months than at baseline in the Treatment group (est =-0.39, se=0.07, *P*<0.001) (Table 3).

Taking NS-E as the reference category, NS-E was not significant for those in the Control group but had a statistically significant effect on MDI scores (est=0.25, se=0.70, *P*<0.001) in the Treatment group. In other words, the effect of NS-E on MDI scores was different for those in the different conditions i.e. an interaction. This interaction was not statistically significant (est=-0.11, se = 0.11, *P*=0.402).

Taking EHLoC as the reference category, EHLoC was positively associated with MDI scores in the treatment condition (est=0.31, se=0.07, *P*<0.001). Additional testing of the difference between the effects of EHLoC in both conditions, indicated this interaction was not significant (est=-0.12, se=0.14, *P*=0.390).

IHLoC (reference category) had a significant effect on MDI scores in both Control and Treatment group. Testing of potential differential effects of IHLoC on MDI scores within the two conditions, indicated the interaction was not statistically significant (est = 0-.169, se = 0.121, *P*= 0.164). IHLoC had no effect upon MDI scores (est=-0.04, se=0.06, *P*=0.467) nor was the interaction statistically significant (est=-0.17, se=0.12, *P*=0.164).

Taking S-RHI as the reference category, S-RHI scores were statistically significantly related to MDI scores for both those in the Control and Treatment groups, with similar effects (est=0.42, se=0.06, *P*<0.001). When the effects of a potential interaction were tested, again, this was not found to be statistically significant (est=-0.03, se=0.12, *P*=0.804) (Table 3).

Estimated Marginal Means (MDI)

The EMM for the MDI score was 5.12 for those in the Control condition at 6 months (SD = 1.63). This was the same score that Controls had at baseline (SD = 1.58). Those in the Treatment group had an EMM of 5.55 (SD = 1.75) at 6 months, while at the baseline the value for this condition was 5.16 (SD = 1.72).

DISCUSSION

Primary analysis of the intervention results found that personalised advice was more effective than non-personalised advice in bringing about healthy dietary change (Celis-Morales *et al.,* 2017). The objective of this analysis has been to evaluate whether Nutrition Self-Efficacy (NS-E), Internal and External HLoC and habit strength (S-RHI) at baseline influenced responses to the intervention. The prediction was that those with higher scores on S-RHI, NS-E and IHLoC and lower scores on EHLoC would be more likely to respond to personalised nutrition advice by making healthy eating choices reflected in higher HEI and MDI scores.

As predicted, results indicated higher NS-E at baseline was associated with higher HEI and MDI scores which increased significantly in the treatment group post-intervention. This is consistent with previous qualitative research which emphasised the importance of motivational factors to personalised nutrition (Stewart-Knox *et al.,* 2013; Rankin *et al.,* 2016) and survey research indicating associations between self-efficacy and attitudes and intention to adopt personalised nutrition (Poínhos *et al.,* 2014). This finding is also consistent with research linking self-efficacy to healthy eating (de Borba *et al.,* 2021; Newby *et al.,* 2020; Lo *et al.,* 2019; Churchill *et al.*, 2019; Naughton *et al.,* 2015; Ferranti *et al.*, 2014; Williams *et al.,* 2012; Anderson *et al.,* 2000). That NS-E did not differ between the control and intervention group post-intervention implies it did not impact upon response to the trial and is contrary to previous studies that have observed increased intake of vegetables (Bouwman *et al.,* 2020), increased fruit and vegetable intake (Smith et al., 2020) and reduced fast food consumption (Smith et al., 2020) in response to enhanced self-efficacy. This could possibly be because average scores were lower than those measured in previous population studies (Naughton *et al.,* 2015; Paxton and Sculthorpe, 1999). This bias was not explained by sample attrition as NS-E did not differ between completers and non-completers (Table 2).

As expected, given previous research linking habit to frequent intake of high energy snacks (Wouters et al., 2018; Naughton *et al.*, 2015) as well as intention to consume a range of foods (Rompotis *et al.,* 2014; de Bruijn and van den Putte, 2009; de Bruijn *et al.,* 2007; Brug *et al.*, 2006; Honkanen and Olsen, 2005; Verbeke and Vackier, 2005), S-RHI scores were associated with higher HEI and MDI. S-RHI also affected response to the intervention and was associated with higher MDI and HEI scores in the Treatment than the Control group post-intervention with moderate effect sizes. This is in keeping with previous interventions which found habit strength to be associated with frequent intake of fruit and vegetables (van Keulen *et al.*, 2021; Bartle *et al.*, 2019) and consumption of sugar-sweetened beverages (Judah et al., 2020). This is also consistent with survey research linking habit to frequent intake of high energy snacks (Wouters et al., 2018; Naughton *et al.*, 2015) and intention to consume a range of foods (Rompotis *et al.,* 2014; de Bruijn and van den Putte, 2009; de Bruijn *et al.,* 2007; Brug *et al.,* 2006; Honkanen and Olsen, 2005; Verbeke and Vackier, 2005). Although scores indicated that our sample were in the mid-range for habit strength (Gardner *et al.,* 2011), they were on average lower than other samples (Naughton *et al.,* 2015). That S-RHI was higher among those who completed the intervention (Table 2), highlights the importance of habit strength to compliance with healthy eating (Gardner *et al.,* 2014) and should be fostered for interventions to be successful. Although S-RHI was associated with higher MDI scores over time, it was not associated with higher MDI scores in the Treatment compared with the Control group post-intervention. This suggests adherence to a Mediterranean diet may be driven more by external factors such as availability and the culture of food (Diaz Mendez *et al.,* 2013; Fleischhacker *et al.,* 2011) and less by individual factors such as habit.

Given previous research (Cheng *et al.*, 2016; Stewart-Knox et al., 2013; Marteau *et al.,* 2010) it was predicted that external (EHLoC) would be negatively associated with dietary indices. That higher EHLoC was associated with higher HEI and MDI scores and over time in the Treatment group, however, agrees with survey research (Jang and Baek, 2018) linking EHLoC to healthier eating. That average EHLoC was higher in our sample than reported in previous studies (Pudrovska, 2015; Paxton and Sculthorp, 1999) could imply a self-selection bias. Higher EHLoC has been associated with greater anxiety (Cheng *et al.,* 2016). It is possible, therefore, that those with higher EHLoC are more anxious to improve their diet and are more likely to volunteer for an intervention despite their EHLoC orientation. This is consistent with analysis of responses from 3811 individuals who provided information about reasons for joining the study and among whom the most common reason (87%) was "concerns for health" (Livingstone *et al.,* 2016c). Previous studies have hinted at sex differences in how EHLoC is related to health behavior (Cobb-Clark *et al.*, 2014; Stewart-Knox *et al.,* 2009). That our sample was balanced by sex, randomised to condition and that no sex differences were observed in responses to any psychological variables at baseline, renders it unlikely that sex affected the result. It is also possible that the unidimensional measure of EHLoC employed failed to capture the construct of externality in its fullest sense (Otto *et al.,* 2011).

Previous research into personalised nutrition has suggested that high internal (IHLoC) could be an important driver of the uptake of and adherence to a personalised diet (Rankin *et al.,* 2016; Poínhos *et al.,* 2014; Cobb-Clark *et al.,* 2014; Stewart-Knox *et al.,* 2009). Contrary to prediction, however, IHLoC was unrelated to either of the dietary indices and did not differ between the control and treatment groups post-intervention. This is also contrary to previous survey research linking IHLoC to healthier eating (Jang and Baek, 2018; Rongen *et al.*, 2014). Average scores on IHLoC were lower and with less variability than those observed in previous population studies (Pudrovska, 2015; Paxton and Sculthorp, 1999). A possible reason for our null results, therefore, could be that because volunteers were self-selected and as such, may have been driven by their low IHLoC which may have affected their responses. Individuals low on IHLoC may have volunteered to obtain extra support to achieve healthy eating. That there were no differences in IHLoC between those who completed and did not complete the intervention supports this theory. Previous studies have also produced null results (von Lengerke *et al.,* 2007; Murphy *et al.,* 2001; Schank and Lawrence, 1993). Where population groups have been studied relationships between IHLoC and health outcomes have tended to be weak (Cheng *et al.,* 2016).

Collecting data on-line may have biased the sample toward those more comfortable with digital solutions. Analysis of the characteristics of those who volunteered (N=5500), however, indicated they were broadly similar to the European (EU) adult population (Livingstone *et al.,* 2016c). Attrition affected the control group to a greater degree than the treatment group (Livingstone *et al.,* 2016c) so that a greater proportion of the sample were in the treatment than the control group. Despite this discrepancy, there remained adequate numbers in both groups to enable meaningful analysis. A strength is that unlike previous dietary health interventions that have recruited from clinical populations (Olsen, 2016), the study employed a non-clinical apparently healthy sample. Another potential limitation inherent in this study is that country of residence was not included as a variable. A sensitivity analysis (see caption table 3) indicated that country had no effect on the interpretation of the fixed affects for either model (HEI or MDI) and suggesting that cross-country differences in Europe have no major influence. This was not surprising given the intervention was delivered on-line and personalised to individuals (not groups), Other studies have also found that once corrected for demographic variables, individuals across Europe share many characteristics (eg.Poínhos *et al.,* 2014), hence, we would not have expected country to have influenced the results.' The lack of ethnic diversity in the final sample, however, limits the degree to which findings can be generalised to the wider EU population. Future research needs to consider more diverse representative samples (Olsen, 2016).

That dietary outcome measures were self-reported may have limited the accuracy of the results. FFQ’s are subject to inaccuracy inherent in recall (MacDiarmid and Blundell, 1998). Electronic dietary assessment such as that used in this research, however, has been found more accurate than ‘paper and pencil’ versions and to produce better compliance (McGloin and Eslami, 2015). The online FFQ used was validated specifically for this project (Fallaize *et al.*, 2014; Forster *et al.*, 2014). The self-reported nature of the psychological measures may also have influenced the results (Fisher, 1993). The use of well-validated psychometric scales for assessment of psychological variables, however, will have gone some way toward reducing response bias.

Only scores on the psychological variables at baseline were included in the analysis so that no account was taken of potential changes following intervention. Given the aim was to determine the influence of pre-existing psychological traits on response to the intervention, we would not expect this to have unduly influenced outcomes. This study has focussed on traits that are enduring in the individual and which may have affected response to the RCT. Despite being collected more than six years previously, these data are appropriate to answer the research question and the time lapse will not have affected the relevance or practical implications of the results. Future research is required to determine any potential feedback loop between psychological factors and personalised nutrition advice.

CONCLUSIONS

Habit Strength appears particularly important to response to personalised nutrition. This analysis has implied that response to the Food4Me intervention was stronger in the Treatment group where HEI was the outcome. Prospective assessment of habit strength for each individua could prove useful in developing and communicating personalised dietary advice most effectively in practice. Personalised nutrition services should contain elements to target and enhance Habit strength taking into account individual barriers to healthy eating, food preferences, lifestyle and social circumstances. Advice may also need tailored so that those with lower habit strength receive additional help in integrating dietary advice into their daily routine and in sustaining healthy changes over time.

Although individual differences in nutrition self-effiacy, external health locus of control and habit strength did not impact upon dietary response to the intervention, they were associated with scores on dietary indices in both the control and intervention groups over the course of the intervention. This suggests that psychological traits will be important to consider in practice when providing nutritional advice (Rozga *et al.*, 2020). Interventions aimed at changing these psychological traits may predict potential openness to future dietary change. Clients may be screened for traits associated with behaviour change during initial consultation so that service delivery, digital interface, goal setting, feedback and monitoring can be tailored to specific individual psychology. These findings also have implications for public health in that interventions should seek to enhance self-efficacy and habit strength in target groups.

To our knowledge, this appears to be the first study that has investigated the impact of psychological traits associated with dietary change on dietary response to personalised nutrition in a European sample of healthy volunteers We hope that these results will encourage others to consider including assessment of psychological constructs that influence dietary change when designing personalised nutrition offerings and in practice.

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Table 1. Mean (*m*) and standard deviation (*sd*) for Healthy Eating Index (HEI), Mediterranean Diet Index (MDI), Self-Report Habit Index (S-RHI), Nutrition Self-Efficacy (NS-E), Internal and External Health Locus of Control (HLoC) scores for individuals randomized to Control (non-personalised advice) and Treatment (personalized nutrition advice) groups at baseline and at 6 months post-intervention.

	Baseline				**Post-Intervention**			
	Control (n=360)		Treatment (n=1120)		Control (n=312)		Treatment (n=958)	
	m	*sd*	*m*	*sd*	*m*	*sd*	*m*	*sd*
HEI	49.59	9.51	49.07	10.02	51.99	9.27	52.99	9.55
MDI	5.17	1.58	5.10	1.72	5.32	1.63	5.58	1.75
IHLoC	3.84	0.70	3.89	0.67	3.78	0.63	3.86	0.67
EHLoC	4.37	0.57	4.42	0.56	4.41	0.60	4.52	0.55
S-RHI	3.30	0.74	3.30	0.78	3.43	0.68	3.45	0.73
NS-E	3.20	0.54	3.24	0.54	3.61	0.71	3.66	0.73

Table 2. Baseline characteristics of those who completed and did not complete the intervention.

	Completers (n=1256)		**Non-Completers** (n=309)		*P* value
	Mean	sd	Mean	sd	
N-SE	3.23	0.54	3.24	0.55	0.833
HLoC	4.14	0.47	4.16	0.49	0.951
IHLoC	3.88	0.68	3.89	0.68	0.542
EHLoC	4.41	0.56	4.43	0.57	0.721
S-RHI	3.33	0.76	3.18	0.82	0.004*

Table 3. Estimates of Fixed Effects for Internal (IHLoC) and External Health Locus of Control (EHLoC), Self-Report Habit Index (S-RHI) and Nutrition Self-Efficacy (NS-E), Healthy Eating Index (HEI) and Mediterranean Diet Index (MDI) outcomes. Interactions for the control and treatment groups at baseline and post-intervention[1].

	Healthy Eating Index (HEI)			**Mediterranean Diet Index (MDI)**		
	Est. (s.e.)	**t**	**p**	**Est. (s.e.)**	**t**	**p**
Intercept	30.66 (2.29)	13.42	<.001	2.08 (.40)	5.15	<.001
Baseline * Control	3.56 (4.41)	.81	.420	1.32 (.78)	1.69	.091
Post-Intervention * Control	5.02 (4.51)	1.11	.265	1.24 (.80)	1.56	.120
Baseline * Treatment	-2.54 (.39)	-6.49	**<.001**	-3.9 (.71)	-5.53	**<.001**
IHLoC * Control	.80 (.58)	1.36	.172	-.21 (.10)	-2.07	.039
IHLoC * Treatment	-.15 (.35)	-.42	.671	-.05 (.06)	-.73	.467
EHLoC * Control	.51 (.70)	.74	.461	.19 (.12)	1.55	.122
EHLoC * Treatment	1.06 (.40)	2.63	**.009**	.31 (.07)	4.38	**<.001**
S-RHI *Control	1.98 (.58)	3.40	**.001**	.39 (.10)	3.76	**<.001**
S-RHI * Treatment	3.42 (.33)	10.37	**<.001**	.42 (.06)	7.16	**<.001**
NS-E * Control	1.06 (.64)	1.66	.098	.14 (.11)	1.21	.225
NS-E * Treatment	1.71 (.39)	4.33	**<.001**	.25 (.07)	3.57	**<.001**

Est=unstandardized estimates; s.e.=standard error

[1]Country of residence was used as a covariate to check if the inclusion of these additional seven variables would have any significant effect on interpretation of the results. Sensitivity analysis indicated that the country covariates made no difference to the statistical significance (0.05 level) of the results. The results, therefore, are reported without the inclusion of country.