# Food-insecure women eat a less diverse diet in a more temporally variable way: Evidence from the US National Health and Nutrition Examination Survey, 2013-4

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## Abstract

Food insecurity is associated with high body weight amongst women, but not men, in high-income countries. Previous research using food recalls suggests that the total energy intake of food-insecure women is not elevated, though macronutrient composition may differ from that of food-secure women. There is limited evidence on temporal patterns of food consumption. Here, we used food recalls from women in the 2013-4 cycle of the National Health and Nutrition Examination Survey (NHANES, n = 2798) to characterise temporal patterns of food consumption in relation to food insecurity. Compared to the food secure, food-insecure women had more variable time gaps between eating; ate a smaller and less variable number of distinct foods at a time; were more variable from day to day in their time of first consumption; were more variable from day to day in the number of times they ate; and consumed relatively more carbohydrate, less protein and less fibre. However, their overall energy intake was no higher. Food-insecure women had higher BMIs (2.25 kg/m$^2$), and around 15% of the BMI difference between food-insecure and food-secure women was accounted for by their more variable time gaps between eating, their lower diversity of foods, and their lower fibre consumption. Food insecurity is associated with measureable differences in the temporal pattern of food consumption, and some of these differences shed light on how food-insecure women come to have higher body weights.

**Introduction**

Food insecurity (FI)—defined as limited or uncertain access to adequate food—is robustly associated with overweight and obesity amongst women, but not men, in high-income countries (Townsend et al. 2001; Nettle, Andrews, and Bateson 2017). Discussions of why this might be the case suggest that experiencing FI promotes greater overall energy intake, specifically by intensifying food motivation (Anselme and Güntürkün 2018; Nettle et al. 2019; Nettle, Andrews, and Bateson 2017). However, the evidence for increased energy intake under FI is less clear than sometimes assumed. For example, a recent review paper (Brunstrom and Cheon 2018) cites experimental evidence from birds as showing that individuals 'increase their food intake when offered access to food at unpredictable times of day' (p. 4). In fact, neither of the studies cited in this passage (Ekman and Hake 1990; Witter and Swaddle 1997) report any data on the birds' food intake; only that the birds had higher masses in the uncertain food condition. Bird studies that do record food intake have found that the weight gain in response to uncertain food occurs with no change in total energy intake (Cuthill et al. 2000), or even whilst total energy intake goes down (Bednekoff and Krebs 1995).

In humans, studies based on participant-reported intake, usually in the form of 24-hr food recalls, have generally concluded that total energy intake does not differ systematically between food-insecure and food-secure women (Bergmans et al. 2018; Kowaleski-Jones, Wen, and Fan 2018; Zizza, Duffy, and Gerrior 2008), or in some cases, that the energy intake of food-insecure women is less (Tarasuk and Beaton 1999). Studies measuring consumption in ways that bypass participant report, by contrast, find that food-insecure individuals consume more calories when given the opportunity to do so. Nettle et al. (2019) gave participants a standardized laboratory 'taste test' of snack foods. They found that food-insecure women (as assessed by questionnaire prior to the study) consumed more calories, though the association was only statistically significant with one of two measures of FI used. Stinson et al. (2018) asked participants to stay in a residential facility and, over 3 days, forage *ad libitum* from vending machines with diverse foodstuffs available. Food-insecure participants ate around 700 kcal per day more than food-secure participants. These two styles of study—the first measuring consumption in the course of ordinary daily life of food that individuals have to purchase for themselves, the second measuring the response to the sudden, short-term availability of free food—may simply capture different processes. The first suffers from the possibility of imprecise or biased reporting, whilst the second suffers from the possibility that the artificial context of the study does not reflect habitual consumption patterns in everyday life, whilst it is those patterns that will determine long-term patterns of weight gain. At present, it is fair to say that the issue of whether FI leads to increases in habitual energy intake is not settled.

However, the food consumption of food-insecure women may differ in other ways than just total energy intake. Using data from the National Health and Nutrition Examination Study (NHANES), Bergmans et al. (2018) found that FI was associated with greater carbohydrate and lesser fibre consumption. Likewise, a number of other studies have found that FI is associated with reduced consumption of fruit, vegetables and dairy products (Hanson and Connor 2014). Even macronutrient composition does not exhaust the potentially relevant features of a pattern of food intake. For example, two experimental studies have shown that the same diet consumed in a temporally irregular rather than a regular pattern causes a lower thermic effect of food (Alhussain, Macdonald, and Taylor 2016; Farshchi, Taylor, and MacDonald 2004). Since the thermic effect of food is a component of energy expenditure, this has implications for weight gain, although participants did not significantly gain weight within the relatively short experimental period of the studies. Correlational evidence suggests that eating fewer meals in the day, and skipping breakfast, are associated with obesity, even after controlling for total energy intake and energetic expenditure from physical activity (Ma et al. 2003).

This evidence raises the possibility that FI may be associated with subtle differences in the temporal pattern of food intake, even if not the total amount, and this may be relevant to the high body weights observed in food-insecure women. There has been a small amount of prior research on this question. Zizza et al. (2008), using NHANES data, found that FI was associated with a reduced number of meals in the day, and consequently larger meal size. However, Zizza et al. (2008) did not measure *variability* in the timing of food consumption. In evolutionary models of energy regulation, it is variability in the timing of food access that is predicted to trigger fat storage, as a buffer against temporary shortfall (Higginson, McNamara, and Houston 2016; Lima 1986; Nettle, Andrews, and Bateson 2017). Moreover, it is variability in the timing of meals, rather than the number of meals per se, that has been shown to reduce energy expenditure via the thermic effect of food (Alhussain, Macdonald, and Taylor 2016; Farshchi, Taylor, and MacDonald 2004). A further limitation of the study by Zizza et al. (2008) is that they did not explore whether the observed differences in food consumption pattern between food-insecure and food-secure individuals mediated the association between FI and body mass index (BMI). Detecting such mediation would be consistent with differences in the temporal pattern of food consumption being not merely correlates of FI, but playing some causal role in the weight gain of food-insecure women.

Here, we investigated in detail the 24-hr food consumption recalls of the adult food-secure and food-insecure women in the 2013-4 cycle of NHANES. Like previous studies, we extracted variables concerning total energy intake, macronutrient composition, and number of eating occasions in the day. Going beyond previous research, we characterised variability over time within each food recall. Temporal variability is of two kinds: intra-day (for example, the variation in time gap or energy intake between the meals of a day), and inter-day (for example eating more, or more often, on some days than other days). Having developed our set of variables characterizing patterns of food consumption, we tested which ones differed between food-secure and food-insecure individuals, both with and without adjustment for sociodemographic characteristics. We then went on to test whether any of the variables that differed by FI were significant statistical mediators of the FI-BMI relationship. Our general predictions were that, compared to food security, FI would be associated with no greater total energy intake; but greater reliance on carbohydrate and less consumption of fibre; fewer meals in the day; greater intra- and inter-day variability in consumption pattern; and a later time of first consumption. We focussed on the women, as it is only in women that an association between FI and body weight is found. We report the parallel analyses for the men in the Appendix. Those analyses may shed light on why the FI-body weight association is lacking in men.

**Materials and Methods**

*The NHANES survey*

NHANES is an ongoing multi-stage survey administered by the National Center for Health Statistics. In each two-year cycle, a large diverse sample of the non-institutionalized US population is recruited to complete a number of questionnaire and examination measures. The sample can be made nationally representative by the application of sampling weights, as is done here (unweighted results are essentially identical). For our main analysis, we selected all adult (18+ years) participants from the 2013-4 cycle who had completed the questionnaire measures and physical examination (n = 5924), then restricted to female gender (n = 3010). Of these women, 2798 had at least one day of 24-hr food recall data. Hence, this is the sample size for analyses involving consumption variables.

*Study variables other than food consumption*

FI was measured using the adult questions of the standard USDA questionnaire (Bickel et al. 2000). This produces a modal score of 0. Hence, in line with previous studies (Kowaleski-Jones, Wen, and Fan 2018), we divided participants into the groups food secure (score of 0; n = 2143) and food

insecure (score > 0; n = 958). Other sociodemographic variables and BMI were captured during the questionnaire and physical examination sessions.

*Food consumption variables derived from 24-hr food recalls*

For food consumption variables, where appropriate, we averaged the two recall days for participants with both days complete (n = 2539). For the remaining 259 participants, variables are based on just one day. In over 99% of cases, day 2 was on a different day of the week to day 1. Thus, pooling the two days helped smooth variability due to day of week.

Values were extracted algorithmically from the food recall files. Foods and beverages consumed are structured in the recall files by consumption event (CE), each CE representing a unique time in the day when something was consumed. Table 1 defines the key variables extracted. The relative carbohydrate, protein, fat, and fibre variables are residuals from regressions of grams of that particular macronutrient consumed on total grams of food consumed. Thus, they represent the amount of each macronutrient consumed, adjusted for that individual's total food consumption, and hence are all uncorrelated with total energy intake. The calculation of residuals was done on the data from both genders combined. Thus, the means for the women are not exactly equal to zero. The inter-day difference (IDD) variables are missing for the 609 participants with only one day of food recall data. These variables are based on unsigned values; that is, they are positive regardless of whether day 2 was greater than day 1 or vice versa.

We did not include variables that were completely predicted by combinations of other variables. For example, the mean time gap between CEs is completely predicted by the time of first CE and the number of further CEs in the day. Hence, it was not necessary to include it separately in the set of variables.

*Data analysis strategy*

For our main analyses, we used multivariate analyses of variance (MANOVAs) to examine whether food-secure and food-insecure women differed on each of three sets of food consumption variables. The sets of variables were: consumption amounts (5 variables concerning total energy intake and macronutrient composition); intra-day pattern (6 variables concerning diversity of foods and variability of consumption within a day); and inter-day variability (5 variables concerning how the two recall days differed from one another). For each set of outcome variables, we performed both a simple and an adjusted MANOVA. For the simple MANOVAs, the sole predictor was FI. For the adjusted MANOVAs, we additionally included age (years), income (% of federal poverty line, NHANES variable INDFMPIR), education (NHANES variable DMDEDUC2), and ethnicity (NHANES variable RIDRETH1) as control variables. To follow up significant MANOVA results and understand which variables in each set were driving any overall differences, we then performed univariate general linear models on each outcome variable separately.

Having established which food consumption variables were significantly predicted by FI after adjustment, we then tested whether any of them predicted BMI, adjusting for income, age, education and ethnicity. Variables that were both predicted by FI and predicted BMI were considered candidate mediators of the FI-BMI association. To test the extent of mediation, we used R package 'lavaan' (Rosseel 2012) to estimate how much of the FI-BMI association operated via the potentially mediating food consumption variables we had identified. We also conducted parallel analyses for the male participants, which are reported in the Appendix. All analyses were conducted in R (R Core Development Team 2018).

**Results**

*Descriptive statistics*

Descriptive statistics for the main food consumption variables are shown in the final column of table 1.

*Main analyses*

Key results are summarised in table 2. For the set of five consumption amount variables, in the unadjusted analysis, there was a significant effect of FI overall.  This was driven by food-insecure women consuming relatively more carbohydrate, less protein, less fat and less fibre than food-secure women. Total energy intake did not differ between food-secure and food-insecure women. In the adjusted analysis, the overall significant difference by FI persisted, though the associations with the individual variables were substantially attenuated. The variables that remained significantly different between food-secure and food-insecure women after adjustment were relative consumption of carbohydrate, protein and fibre.

For the six variables concerning intra-day patterning of consumption, there was a significant difference between the food-secure and food-insecure women overall in the unadjusted analysis. This was driven by food-insecure women having their first CE later; having fewer CEs in the day; fewer distinct foods per CE; a less variable number of distinct foods per CE; more variable time gaps between CEs; and more variability in energy per CE. The overall significant difference between food-secure and food-insecure women persisted in the adjusted analysis. Amongst the individual variables, the differences in time of first CE, number of CEs, and variability in energy per CE were attenuated to the point of non-significance by the adjustment. Thus, after adjustment, significant differences between food-insecure and food-secure women persisted in the mean and variability of foods per CE, and the variability of the time gap between CEs.

For the variables based on inter-day differences in pattern, the effect of FI in the MANOVA was significant both adjusted and unadjusted. In the unadjusted analysis, food-insecure women differed from food-secure women by having greater inter-day difference in total energy intake; greater inter-day difference in the time of the first CE; greater inter-day difference in the number of CEs; and a greater inter-day difference in the mean time gap between CEs. After adjustment, only the inter-day difference in the time of the first CE and the inter-day difference in the number of CEs remained significantly associated with food insecurity.

To visualize the results, and establish which variables were most strongly associated with FI, we standardized parameter estimates from all of the adjusted univariate analyses, and produced a forest plot (figure 1).  Variables are sorted by (unsigned) size of the parameter estimate, so that variables more strongly associated with FI appear higher on the figure.

Table 1. Variables extracted from the food recalls. CE: Consumption event. IDD: Inter-day differences (for participants with two separate days of food recall data).

| | Variable name | Definition | Units | Women's mean (sd) |
|---|---|---|---|---|
| Consumption amounts | Energy intake | Total energy intake per day | Kcals | 1779 (704) |
| | Relative carbohydrate | Relative carbohydrate | g | 2.61 (30.20) |
| | Relative protein | Relative protein | g | -3.26 (19.93) |
| | Relative fat | Relative fat | g | 0.43 (18.76) |
| | Relative fibre | Relative fibre | g | 0.23 (6.60) |
| Intra-day pattern | First CE | Time of first CE | Hours from midnight | 7.93 (2.27) |
| | Number of CE | Number of CEs per day | Number | 5.57 (1.63) |
| | Mean foods per CE | Mean number of distinct foods per CE | Number | 9.68 (3.28) |
| | Variability foods per CE | Intra-day standard deviation number of distinct foods per CE | Number | 5.42 (1.93) |
| | Variability time gap | Intra-day standard deviation in time gap between CEs | Minutes | 104.27 (48.79) |
| | Variability energy per CE | Intra-day standard deviation Kcals per CE | Kcals | 322.2 (152.65) |
| Inter-day variability (participants with 2 days of data) | IDD energy intake | Inter-day difference in energy intake | Kcals | 627.91 (577.70) |
| | IDD first CE | Inter-day difference in time of first CE | Hours | 1.65 (2.15) |
| | IDD number of foods | Inter-day difference in number of foods | Number | 4.61 (3.84) |
| | IDD number of CEs | Inter-day difference in number of CEs | Number | 1.48 (1.32) |
| | IDD mean time gap | Inter-day difference in mean time gap between CEs | Minutes | 63.42 (70.67) |

Table 2. Parameter estimates for the difference between food-secure and food-insecure women. Adjusted models include income, education, ethnicity and age as additional predictors. Food secure is the reference category and hence the parameter estimates represent the deviation of food-insecure women from the food-secure mean.

| | Unadjusted | | Adjusted | |
|---|---|---|---|---|
| | B (se) | p-value | B (se) | p-value |
| *Consumption variables* | *MANOVA F(5, 2792) = 21.52* | *< 0.001* | *MANOVA F(5, 2580) = 21.94* | *< 0.001* |
| Energy intake | 6.74 (29.55) | 0.82 | -5.67 (34.32) | 0.87 |
| Relative carbohydrate | 9.92 (1.34) | <0.001 | 4.31 (1.55) | 0.006 |
| Relative protein | -4.50 (0.99) | <0.001 | -2.63 (1.04) | 0.01 |
| Relative fat | -3.22 (0.81) | <0.001 | -0.88 (0.94) | 0.35 |
| Relative fibre | -2.02 (0.28) | < 0.001 | -0.80 (0.31) | 0.01 |
| *Intra-day pattern variables* | *MANOVA F(6, 2685) = 24.68* | *< 0.001* | *MANOVA F(6, 2483) = 27.65* | *< 0.001* |
| First CE | 0.25 (0.09) | 0.007 | -0.14 (0.11) | 0.19 |
| Number of CEs | -0.50 (0.07) | < 0.001 | -0.12 (0.08) | 0.15 |
| Mean foods per CE | -1.49 (0.14) | < 0.001 | -0.43 (0.16) | 0.006 |
| Variability foods per CE | -0.90 (0.09) | < 0.001 | -0.29 (0.10) | 0.002 |
| Variability time gap | 16.15 (2.07) | < 0.001 | 9.55 (2.39) | <0.001 |
| Variability energy per CE | 22.07 (6.48) | < 0.001 | 10.41 (7.47) | 0.16 |
| *Inter-day variability variables* | *MANOVA F(5, 2516) = 8.96* | *<0.001* | *MANOVA F(5, 2328) = 9.23* | *<0.001* |
| IDD energy intake | 65.15 (25.91) | 0.01 | 17.70 (30.50) | 0.56 |
| IDD first CE | 0.52 (0.09) | <0.001 | 0.28 (0.11) | 0.01 |
| IDD number of foods | 0.05 (0.18) | 0.79 | 0.33 (0.21) | 0.12 |
| IDD number of CEs | 0.11 (0.06) | 0.06 | 0.15 (0.07) | 0.03 |
| IDD mean time gap | 13.32 (3.26) | <0.001 | 4.83 (3.78) | 0.20 |
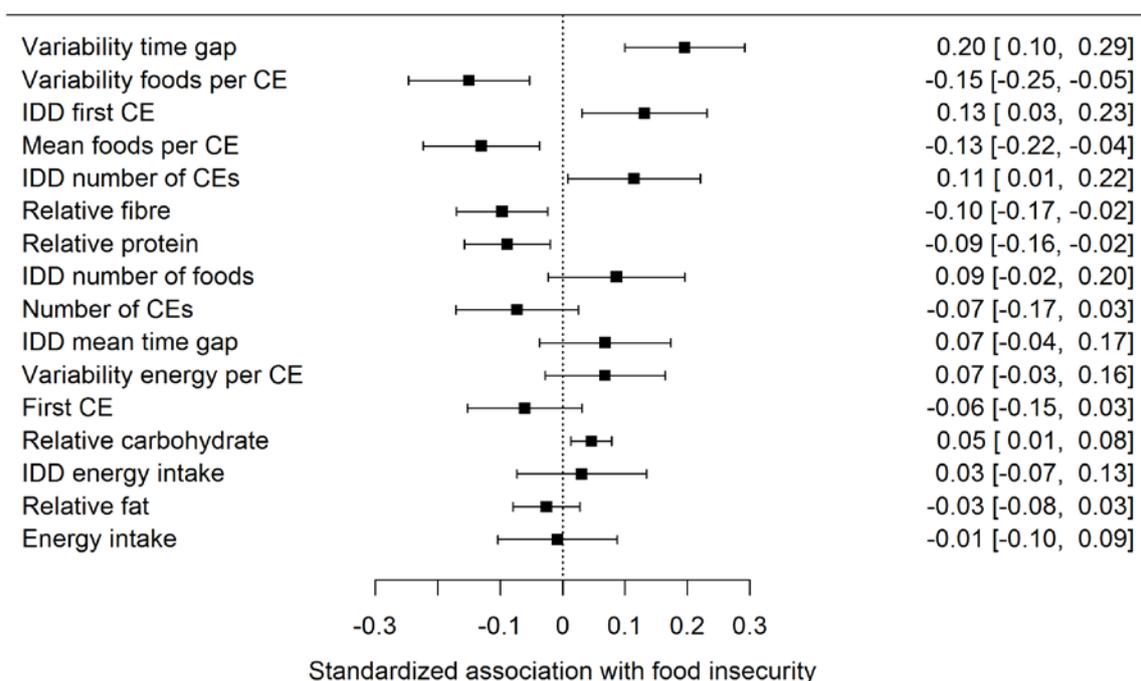
Figure 1. Forest plot of standardized associations between food insecurity status and food consumption variables for NHANES women, after adjustment for age, income, education and ethnicity. Variables are sorted so that those more strongly associated with food insecurity status appear higher on the figure. A negative value indicates that food-insecure women have a lower value of the parameter, and a positive value a higher value. Whiskers represent 95% confidence intervals. CE: Consumption event. IDD: Inter-day difference (for participants with two separate days of recall data).

Table 3. Results of models testing whether each of the food consumption variables significantly associated with food insecurity predicts body mass index in NHANES women. All models are adjusted for age, income, education and ethnicity.

| Predictor | B (se) | p-value |
|---|---|---|
| Relative carbohydrate | -0.01 (0.005) | 0.06 |
| Relative protein | 0.01 (0.005) | 0.05 |
| Relative fibre | -0.12 (0.03) | <0.001 |
| Mean foods per CE | -0.11 (0.05) | 0.02 |
| Variability foods per CE | 0.01 (0.08) | 0.87 |
| Variability time gap | 0.01 (0.003) | 0.005 |
| IDD first CE | 0.003 (0.008) | 0.97 |
| IDD number of CEs | 0.02 (0.12) | 0.88 |

*Mediation of the FI-BMI association*

Food-insecure women had higher BMIs than food-secure women (insecure: mean 31.13, sd 8.86; secure: mean 28.77, sd 7.37). This constituted a significant difference after adjustment for income, education, ethnicity and age (B = 1.50, se 0.38, p < 0.001).

We explored whether the food consumption variables we had identified as robustly associated with FI could serve as mediators of the association between FI and BMI. We ran models testing whether each of the eight variables with parameter estimates significantly different from zero in figure 1 predicted BMI, after adjustment for age, income, education and ethnicity (table 3). Three of the variables (variability time gap, mean foods per CE, and relative fibre consumption) significantly predicted BMI, after adjustment, in the correct direction to serve as a potential mediator. Relative protein consumption also near-significantly predicted BMI, but in the wrong direction to mediate the FI-BMI association (higher protein, higher BMI).

We then created a multiple mediation model with BMI as the outcome, FI as the predictor, and variability time gap, mean foods per CE, and relative fibre consumption as the mediators. There was an overall positive effect of FI on BMI (total effect 2.21, s.e. 0.33, z = 6.77, p < 0.001). The pathways via the three mediators accounted for 14.5% of the effect of FI on BMI. This was respectively composed of 4.2% via variability time gap (z = 2.17, p = 0.03), 2.9% via mean foods per CE (z = 1.04, p = 0.30) and 7.4% via fibre consumption (z = 3.33, p = 0.01).

**Discussion**

Using 24-hr food recalls from participants in the large, nationally representative NHANES survey, we found that total energy intake was no higher in food-insecure than food-secure women. However, patterns of food consumption differed in many other ways. Specifically, food-insecure women had more variable time gaps between eating; ate a smaller and less variable number of distinct foods at a given consumption event; were more variable from day to day in their time of first consumption in the day; were more variable from day to day in the number of times they ate; and consumed relatively more carbohydrate, less protein and less fibre. These differences were robust to control for age, income, education and ethnicity. Thus, food-insecure women eat a diet that is less diverse than that of food-secure women, but do so in a more temporally variable way. We found that three of the food-consumption differences between food-insecure and food-secure women—their more variable time gaps between eating, their lower number of distinct foods per consumption event, and their lower fibre consumption—partially accounted for their greater body masses.

These findings are informative on several different levels. At the simplest level, they can be seen as a validation of the FI questionnaire measure. For example, the questionnaire probes whether, over the 12 months prior to responding, the respondent sometimes had to skip meals, sometimes ran out of food, or was unable to eat balanced meals (Bickel et al. 2000). We can indeed detect, in the detailed food recalls, that food-insecure women had more variable gaps between meals and relied on a smaller number of foods. The relatively high carbohydrate composition and low protein and fibre composition suggest a reliance on cheap sources of calories and low consumption of vegetables, fruit and dairy. This pattern would be expected where budgets for obtaining food are highly constrained (Drewnowski and Specter 2004), and is consistent with previous studies of FI (Hanson and Connor 2014; Bergmans et al. 2018). Our findings suggest that when food-insecure women responded in the affirmative to the FI questions, they were not, overall, just misremembering, exaggerating or interpreting the question content idiosyncratically. Their reported food consumption behaviour was systematically different from those who did not respond in the affirmative to the

food-insecurity questions, even after adjusting for their different sociodemographic characteristics. The food recalls were self-reported too, of course, but represent a very different kind of measure from the general statements of the FI questionnaire.

More deeply, the findings bear on the question of how FI may lead to high body weight in women in developed countries. The results here concur with those of similar investigations (Bergmans et al. 2018; Kowaleski-Jones, Wen, and Fan 2018; Zizza, Duffy, and Gerrior 2008) in that food-insecure women did not appear to have higher total energy intake. Stinson et al. (2018) suggest that the failure to find excess energy intake in food-insecure women in dietary recall studies is to do with the limitations of participant report. For this explanation to be correct, there would have to be not just biased reporting, but differentially biased reporting by FI status, in self-report consumption measures. This is plausible, since differential under-reporting of energy intake has been in obese individuals (Schoeller 1995) and individuals of lower socioeconomic status (Carter and Whiting 2010). However, the recall data used here were adequate to identify numerous other significant differences between the food-consumption patterns of food-insecure and food-secure individuals, spanning from what they ate to when they ate it. It is unclear why participant-recalled data would be adequate to reveal all these other differences, but uniquely inadequate to reveal differences in total energy intake. An alternative possibility is that habitual total energy intake is really no higher in food-insecure women. In this case, the increase consumption observed in staged eating opportunities (Nettle et al. 2019; Stinson et al. 2018), though real, might represent a short-term response to free food amongst people used to being highly constrained in what they can procure.

If habitual total energy intake were not increased amongst food-insecure women, this would not undermine the general principle that weight gain is an adaptive response to FI (Lima 1986; Higginson, McNamara, and Houston 2016). In fact, our findings partly justify the linkage made by Nettle et al. (2017) between the human FI literature and experimental studies of uncertain food access in animals (Ekman and Hake 1990; Witter and Swaddle 1995; Witter, Swaddle, and Cuthill 1995; Zhang et al. 2012). In the animal experiments, uncertain food access is usually operationalised as variable time gaps between accesses to food, which is shown to lead to mass gain, sometimes without any concomitant increase in total energy intake (Cuthill et al. 2000). The present study is the first to show that food-insecure people—as measured by the conventional human FI questionnaire measure—also experience more variable time gaps between food consumption. Though food-insecure women also differ from food-secure in *what* they eat, the variable that showed the most marked difference between food-insecure and food-secure women in figure 1 was the variability in *when* they eat it. This is very close to the variable that is experimentally manipulated in the animal studies. This suggests that FI as it is studied in the social sciences is indeed a related phenomenon to the uncertain food access studied in behavioural ecology.

Although we found some support for the contention that differences in food consumption patterns statistically mediate the association between FI and body weight in women, the extent of the mediation was weak. Between them, the three mediating variables accounted for less than 15% of the association between FI and body weight. At face value, this implies we largely failed to identify what it is that makes food-insecure women become heavier than food-secure women. However, the mediation pathways we identified may be more important than the 15% figure suggests. The food consumption variables here are based on only one or two days of data for each participant. Certain patterns—for example, rare but serious hunger, or end-of-the-month food shortages—are relatively unlikely to be captured by the food recalls because they do not happen on most days. Many food-insecure respondents might appear to consume regularly from just two days of recall, when a longer period of study would identify important but infrequent temporal irregularities. Thus, our measures of variability in food access under-detect many important kinds of variation. As such, we would expect the measured associations between FI and food consumption variability, and also between

food consumption variability and body weight, to be underestimates of the true associations. Viewed in this light, rather than seeing it as a shortcoming that we can only account for 15% of the FI-body weight relationship, we find it noteworthy that from just two days of food recalls, we can detect numerous significant differences between food-insecure and food-secure women, and that some of these statistically mediate any of the excess body weight of food-insecure women.

Nonetheless, there are likely to be important differences between food-insecure and food-secure women not captured in our set of food-consumption variables. Most obviously, we have included no measures relating to physical activity. This is a major limitation. It is quite plausible that FI leads to reductions in physical activity and hence energy expenditure (Lee and Cardel 2018). The evidence for this in humans is currently sparse, though there are suggestive data from animal experiments (Zhang et al. 2012; Dall and Witter 1998). Thus, our study cannot determine whether energy intake relative to energy expenditure is greater in food-insecure women; presumably, this must be the case, given the higher body weights. Experimental studies in which participants are assigned to iso-caloric diets that involve either temporally regular or temporally irregular intake find that irregularity reduces energy expenditure via a diminished thermic effect of food (Alhussain, Macdonald, and Taylor 2016; Farshchi, Taylor, and MacDonald 2004). This mechanism could potentially explain why we found evidence for a mediating role of temporal consumption irregularity in the FI-body weight relationship, although the NHANES data do not allow us to test this directly as they include no measure of the thermic effect of food.

Our findings do not provide a clear picture of why FI leads to high body weight in women but not men. Patterns of food consumption differed between food-insecure and food-secure individuals among men in very similar ways to women (see Appendix). The differences were of similar magnitude (across our 16 variables, the mean of the unsigned standardized effect size for the food-insecure to food-secure comparison was 0.09 for the women and 0.07 for the men). Moreover, food consumption variables predicted body weight amongst men in much the same way they did amongst women (see Appendix). The only notable difference was in the case of the variability in time gap between CEs. In women, a greater variability in time gap was clearly associated with a higher BMI. In men, the corresponding association was null. Thus, it is possible that women respond physiologically to variability in the time gap between food intake in a way that men do not. However, this effectively restates the sex difference in the response to FI via a different variable: it does not, in itself, explain that sex difference.

**Conclusions**

In a large, nationally representative US sample, we have shown that FI, as measured by the USDA questionnaire, corresponds to measurably different patterns of food consumption. In line with previous studies, we found that food-insecure women eat more carbohydrate, and less protein and fibre, but appear to consume the same amount of energy overall. We also showed that they had a lower diversity of foods, and, critically, that they showed greater temporal variability in their intake. These variations in food consumption patterns may be part of the reason that food-insecure women end up with higher body weights.

**Data availability**
The NHANES 2013-4 data are downloadable from https://wwwn.cdc.gov/nchs/nhanes/Default.aspx. The R code required to reproduce all our analyses, or perform other analyses with the derived variables we created, is freely available on the Zenodo repository at: https://doi.org/10.5281/zenodo.2649031. The repository submission includes information on which NHANES files are required.

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**Appendix: Analysis of data from male participants**

We repeated the analyses conducted on the female data on the data from the male participants from the NHANES 2013-4 cycle (n = 2558; 2208 with 2 days of food recall data, 350 with 1 day). Table S1 presents the parallel analyses to table 2 for the men, and figure S1 shows the male equivalent of figure 1.

Results were in many respects similar for the men as for the women. All three MANOVAs showed significant differences between food-insecure and food-secure men, both adjusted and unadjusted. The individual variables showing strong directional differences in the women also tended to do so in the men (correlations, across variables, between male and female standardized effect sizes, r = 0.66, p < 0.001). Of the eight individual variables showing a significant association with FI after adjustment in the women, five also did so in the men (relative carbohydrate, relative protein, relative fibre, mean foods per CE, variability foods per CE). These associations were all in the same direction in the two genders. The remaining three variables that showed a significant difference by FI in the women showed no significant difference by FI in the men (variability time gap, IDD first CE, IDD number of CEs). One of these (variability time gap) was only marginally non-significant, and in the same direction as in the women. Thus, the pattern of differences in food consumption variables between food-insecure and food-secure individuals appears similar across men and women. We have also confirmed that FI affects both genders similarly by combining the male and female data and running models with FI, gender and their interaction as predictors. We generally found main effects of FI, rather than interactions between FI and gender (data not shown).

We confirmed that FI does not predict BMI in the men, either in unadjusted (B = 0.007, se 0.28, p = 0.98) or adjusted (B = 0.15, se 0.63, p = 0.64) analyses.

We repeated the analyses of table 3 of the main paper – that is, analyses of which food consumption variables predicted BMI – for the men (table S2). There were actually more food consumption variables significantly associated with BMI for men than women (five significant associations for men versus four for women), and generally the same ones in the same directions (women: relative protein, relative fibre, mean foods per CE, variability time gap; men: relative carbohydrate, relative protein, relative fibre, mean foods per CE, variability foods per CE). Variability in time gap was not significantly associated with BMI in the men, whereas it was one of the mediating variables in the women. Thus, of the three food consumption variables that partially mediate the FI-BMI association in the women (relative fibre consumption, mean foods per CE, variability time gap), two (relative fibre consumption and mean foods per CE) are associated both with FI and with BMI in men, just as they are in women. The only difference is that they cannot serve as statistical mediators, since there is no overall association to mediate. The third (variability in time gap), which was a partial mediator in women, was marginally non-significantly associated with FI, and non-significantly associated with BMI, in the men.

Table S1. Parameter estimates for the difference between food-secure and food-insecure men. Adjusted models include income, education, ethnicity and age as additional predictors. Food secure is the reference category and hence the parameter estimates represent the deviation of food-insecure women from the food-secure mean.

| | Unadjusted | | Adjusted | |
|---|---|---|---|---|
| | B (se) | p-value | B (se) | p-value |
| *Consumption variables* | *MANOVA F(5, 2552) = 19.46* | *< 0.001* | *MANOVA F(5, 2352) = 21.57* | *< 0.001* |
| Energy intake | 135.37 (43.55) | 0.002 | 51.42 (51.08) | 0.32 |
| Relative carbohydrate | 12.42 (1.96) | <0.001 | 6.92 (2.31) | 0.003 |
| Relative protein | -5.53 (1.41) | <0.001 | -4.07 (1.65) | 0.01 |
| Relative fat | -4.15 (1.12) | <0.001 | -1.59 (1.31) | 0.22 |
| Relative fibre | -2.74 (0.37) | < 0.001 | -1.26 (0.41) | 0.002 |
| *Intra-day pattern variables* | *MANOVA F(6, 2416) = 20.96* | *< 0.001* | *MANOVA F(6, 2229) = 22.57* | *< 0.001* |
| First CE | 0.45 (0.11) | <0.001 | 0.11 (0.13) | 0.37 |
| Number of CEs | -0.49 (0.08) | <0.001 | -0.14 (0.09) | 0.14 |
| Mean foods per CE | -1.61 (0.16) | <0.001 | -0.37 (0.17) | 0.03 |
| Variability foods per CE | -0.94 (0.09) | <0.001 | -0.28 (0.10) | 0.006 |
| Variability time gap | 13.58 (2.79) | <0.001 | 6.44 (3.34) | 0.05 |
| Variability energy per CE | 34.74 (9.72) | <0.001 | 3.42 (11.50) | 0.77 |
| *Inter-day variability variables* | *MANOVA F(5, 2186) = 11.02* | *<0.001* | *MANOVA F(5, 2023) = 10.05* | *<0.001* |
| IDD energy intake | 189.12 (37.41) | <0.001 | 80.18 (44.06) | 0.07 |
| IDD first CE | 0.36 (0.13) | 0.008 | -0.12 (0.16) | 0.44 |
| IDD number of foods | -0.004 (0.21) | 0.99 | 0.008 (0.25) | 0.97 |
| IDD number of CEs | -0.01 (0.07) | 0.83 | -0.07 (0.08) | 0.42 |
| IDD mean time gap | 17.61 (3.74) | <0.001 | 2.68 (4.45) | 0.54 |
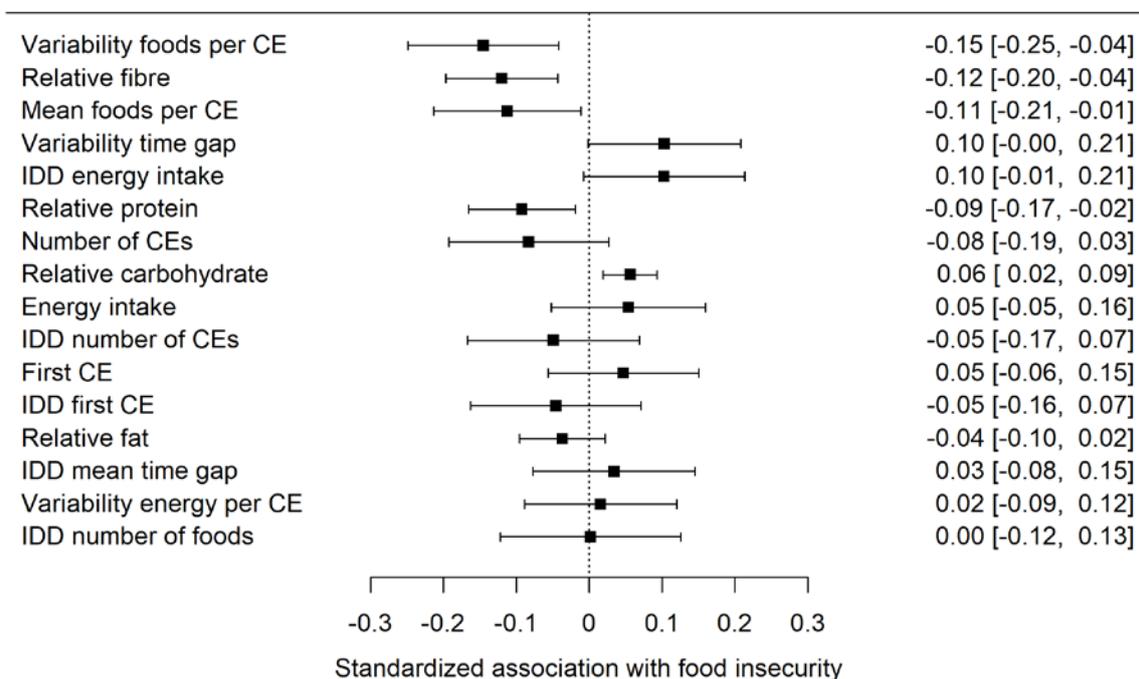
Figure S1. Forest plot of standardized associations between food insecurity status and food consumption variables for NHANES men, after adjustment for age, income, education and ethnicity. Variables are sorted so that those more strongly associated with food insecurity status appear higher on the figure. A negative value indicates that food-insecure women have a lower value of the parameter, and a positive value a higher value. Whiskers represent 95% confidence intervals. CE: Consumption event. IDD: Inter-day difference (for participants with two separate days of recall data).

Table S2. Results of models testing whether each of the food consumption variables significantly associated with food insecurity predicts body mass index in NHANES men. All models are adjusted for age, income, education and ethnicity.

| Predictor | B (se) | p-value |
|---|---|---|
| Relative carbohydrate | -0.01 (0.003) | 0.002 |
| Relative protein | 0.01 (0.004) | 0.03 |
| Relative fibre | -0.04 (0.02) | 0.03 |
| Mean foods per CE | -0.25 (0.04) | <0.001 |
| Variability foods per CE | -0.23 (0.07) | 0.001 |
| Variability time gap | 0.002 (0.002) | 0.42 |
| IDD first CE | -0.02 (0.05) | 0.78 |
| IDD number of CEs | 0.006 (0.10) | 0.95 |