A Cost Constraint Alone Has Adverse Effects on Food Selection and Nutrient Density: An Analysis of Human Diets by Linear Programming[1]

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ABSTRACT Economic constraints may contribute to the unhealthy food choices observed among low socioeconomic groups in industrialized countries. The objective of the present study was to predict the food choices a rational individual would make to reduce his or her food budget, while retaining a diet as close as possible to the average population diet. Isoenergetic diets were modeled by linear programming. To ensure these diets were consistent with habitual food consumption patterns, departure from the average French diet was minimized and constraints that limited portion size and the amount of energy from food groups were introduced into the models. A cost constraint was introduced and progressively strengthened to assess the effect of cost on the selection of foods by the program. Strengthening the cost constraint reduced the proportion of energy contributed by fruits and vegetables, meat and dairy products and increased the proportion from cereals, sweets and added fats, a pattern similar to that observed among low socioeconomic groups. This decreased the nutritional quality of modeled diets, notably the lowest cost linear programming diets had lower vitamin C and β-carotene densities than the mean French adult diet (i.e., <25% and 10% of the mean density, respectively). These results indicate that a simple cost constraint can decrease the nutrient densities of diets and influence food selection in ways that reproduce the food intake patterns observed among low socioeconomic groups. They suggest that economic measures will be needed to effectively improve the nutritional quality of diets consumed by these populations. J. Nutr. 132: 3764–3771, 2002.

KEY WORDS: • *linear programming* • *nutrient* • *diet cost* • *food selection* • *adults*

Poor-dietary quality is common among low socioeconomic status (SES)[3] groups (1). Low fruit and vegetable consumption resulting in suboptimal nutrient intakes, notably for vitamin C and β-carotene, has been consistently reported for low SES groups (2–10). Such diet patterns could play a role in the social gradient of health noted in industrialized countries (2,11). Increased risks of cancers (12) and cardiovascular diseases (13,14) have been found in individuals consuming very low amounts of fruit and vegetables. In addition, there is a strong inverse relationship between vitamin C status and all-cause mortality (15).

The reasons underlying the unhealthy food choices made by individuals from low SES groups in industrialized countries are not fully understood. Nutrition knowledge and beliefs may play a role (16,17). However, material and economic constraints are probably also involved because they can affect health indirectly via their influence on behavior, including dietary habits (18). Insufficient food storage space and avoidance of food wastage were previously identified as factors reinforcing unhealthy eating in low income families (19), as well as the known pricing inequities between small local shops and large supermarkets that are only accessible by automobile (20,21). Dietary quality assessed by a global index has been shown to decline when less money is spent on food (22). Clearly the price of food, although not systematically perceived as a barrier to healthy eating (23), is an important determinant of food choice, especially among low income groups and the unemployed (24,25).

In the present study, the impact of food budget (i.e., diet cost) on food selection patterns and dietary quality was investigated using a mathematical modeling technique: linear programming (LP). The advantage of LP is that it can be used to help explain observational studies by modeling underlying structures of food choice, independent of social or cultural factors or the declaration bias inherent to dietary surveys. Notably differences in nutrition skills across social strata may contribute to a differential declaration bias for fruit and vegetable consumption among advantaged compared with disadvantaged groups (26), and a bias in reported income levels may attenuate existing relationships. Such confounding effects can be difficult to control even with a multivariate analysis. In human nutrition the main application of LP has been to identify low cost nutritious diets for populations in different countries (27–30). In the present study, it was instead used as an alternative method to simulate the impact of varying one isolated factor (i.e., diet cost) on other variables (i.e., food

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[3] Abbreviations used: LP, linear programming; PRI, population reference intakes; PUFA, polyunsaturated fatty acids; SES, socioeconomic status; TDMI, total departure from the mean food intake.

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composition and nutrient density of the diet). The objectives of this study were therefore to develop LP models to predict the food choices a rational individual would make to reduce the amount of money spent on food and to evaluate the impact of this cost constraint on nutritional quality.

METHODS

Dietary data, food composition database and food prices

The input data used to design the LP diets were dietary data collected in a cross-sectional survey from 1108 randomly selected persons between the ages of 6 mo and 97 y residing in the district of Val de Marne, located in the Paris area (France) (31). Only data collected from adults aged ≥18 y old (361 men and 476 women) were used in the present study. As previously described (31), usual food intakes were estimated using the diet history method completed in each participant's home by trained dieticians. The French food composition table containing 73 food items and 28 nutrients adapted for the purpose of the survey was used in the present study. An estimated price for each food was also added to this food composition database. These prices were taken from the 2000 mean retail prices in France published by the INSEE (Institut National de la Statistique et des Etudes Economiques) (32), completed when necessary by mean prices taken from three or four supermarkets in the Paris area.

Designing diets by LP

LP for designing diets has been described in greater detail elsewhere (33). In the present study LP models were developed to obtain isoenergetic diets (expressed as food intakes/d) for each gender that incrementally decreased in cost. The total energy content of these LP diets was fixed at a constant level by an equality constraint. Constraints were also introduced in all models to ensure global consistency of the LP diets with actual food consumption patterns of French adults. Total departure from the mean food intake observed in the population was minimized, while a cost-constraint was introduced and progressively strengthened. In other words, for each gender and each total diet cost, the objective was to design an LP diet that most closely resembled the mean diet observed in the population while fulfilling all the constraints: energy, food and food groups. The impact of the cost constraint on food selection and nutritional quality was assessed by analyzing the food composition and the nutrient densities of the LP diets. All LP models were run with the Simplex procedure of the Premium Solver 3.5 for Excel (Frontline System, Incline Village, NV).

Definition of the objective function. LP is defined by the maximization or minimization of a linear function, called the objective function, which is dependent on a set of decision variables restricted by various linear constraints. To be linear in relation to decision variables $X_1, X_2 \ldots X_n$, an objective function Y must be expressed in the following form

$$Y = a_0 + a_1X_1 + a_2X_2 + \ \ldots\ + a_nX_n, \quad \text{where} \quad a_0, a_1, a_2 \ldots a_n \quad \text{are constants} \qquad (I)$$

In the present study, the objective function was designed to minimize departure from the mean diet observed in the French adult population. This assumes that individuals facing economic constraints choose diets that conform as close as possible to the average food intake of the population. We believe this is a valid assumption because sociological and ethnological observations have shown that the poor maintain their identity and self-respect by retaining familiar dietary patterns, instead of purchasing the cheapest source of nutrients to achieve a healthy diet (34).

A function called "total departure from the mean food intake" (TDMI) was created for this purpose. It was defined as the sum of the absolute values of differences between each food variable portion size selected by LP X_i (with $i = 1$ to n, where n is equal to the total number of foods in the database) and the mean portion sizes m_i observed in the French population for the related food (calculated for men and women separately), divided by m_i, as follows:

$$\text{TDMI} = \text{ABS}(m_1 - X_1)/m_1 + \text{ABS}(m_2 - X_2)/m_2 + \ \ldots\ + \text{ABS}(m_n - X_n)/m_n$$

The difference between X_i and m_i was divided by m_i to standardize the difference across foods. This expression of TDMI, although the most meaningful, was a nonlinear function of X_i because of the absolute value calculation. However, to guarantee the global optimum per analysis (33), each model has to be analyzed by LP and therefore must exclusively include linear functions. Hence TDMI was transformed into a linear function. For this purpose, new decision variables Z_1 to Z_n were created and were subjected to the following constraints:

$$Z_1 \geq (m_1 - X_1)/m_1 \quad \text{and} \quad Z_1 \geq -(m_1 - X_1)/m_1,$$

$$Z_2 \geq (m_2 - X_2)/m_2 \quad \text{and} \quad Z_2 \geq -(m_2 - X_2)/m_2 \ldots$$

$$Z_n \geq (m_n - X_n)/m_n \quad \text{and} \quad Z_n \geq -(m_n - X_n)/m_n$$

Therefore for each standardized difference, its positive value (i.e., its absolute value) was selected because Z_i by definition has to be greater than or equal to both the standardized difference and its opposite value. The sum of Z_i was thus equivalent to TDMI, without the need for the absolute value term, and was a linear function of X_i.

This is shown below, using an example in which all standardized differences $(m_i - X_i)/m_i$ are positive. In this case, the sum of all Z_i becomes

$$\Sigma Z_i = (m_1 - X_1)/m_1 + (m_2 - X_2)/m_2 + \ \ldots\ + (m_n - X_n)/m_n,$$

which is equivalent to

$$\Sigma Z_i = [1 - (1/m_1)X_1] + [1 - (1/m_2)X_2] + \ \ldots\ + [1 - (1/m_n)X_n],$$

which is equivalent to

$$\Sigma Z_i = n - (1/m_1)X_1 - (1/m_2)X_2 - \ \ldots\ - (1/m_n)X_n$$

This final transformation is identical to the linear equation I presented above. In this case, the sum of Z_i is equivalent to Y, with $a_0 = n$ and $a_i = -(1/m_i)$.

The sum of Z_i was therefore chosen as the objective function and minimized by LP. An additional advantage of using the sum of Z_i as the objective function was that it avoided the use of a nonlinear quadratic function.

Introduction of constraints on energy, food portions and food-groups. The energy content of each LP diet was fixed to equal the mean daily energy intakes observed in the population: 9.8 MJ (2347 kcal) for men and 7.3 MJ (1748 kcal) for women. This constraint was based on the assumption that total food intake is determined by energy and not nutrient requirements and on the observation that diet quality is affected before diet quantity in food-insufficient households (35). In addition, designing isoenergetic diets allowed comparisons across LP diets.

Food constraints were applied to all models to ensure that LP diets were compatible with the observed dietary patterns in the population. First, an upper limit was placed on the portion size for each food variable to avoid selection of food quantities outside the range usually eaten in the population. These daily portions (in g/d) were limited to the 75th percentiles of the consumer intake distribution, that is, distribution of quantities consumed by adults (men and women together) who consumed the food. Second, constraints on the minimal and maximal quantities of energy contributed by different food groups and subgroups were introduced for each gender based on observed intake distributions to ensure accordance with actual French diet patterns. Food items in the database were classified into one of six main groups (and 21 subgroups) defined as follows: fruit and vegetables, meat/fish/eggs, dairy, cereals, added fats and sweets. For both genders, the energy contributed by each food group was limited to between the 10th and 90th percentiles of the population distribution. These percentile cutoffs were calculated separately in the population of men and women to take into account the differences in food pattern intakes observed between genders. Likewise the energy contributed by each food subgroup was limited to between the 5th and 95th percentiles of the population distribution, calculated for men and women separately. Third, to avoid an unrealistic diet, foods rarely consumed by the population were excluded from the LP diets, by setting the maximal daily portions of food items consumed by <10% of the population to zero. Water, alcoholic beverages, tea and coffee were also excluded. This reduced the number of eligible food items for diet modeling from 73 to 54 in men and to 56 in women.

Introduction of a cost constraint. The LP diet that was nearest to the mean diet observed in adults was first obtained. A constraint limiting the total cost of the diet (a linear function of food weights) in € (1 € = 0.99 U.S. $) was then introduced and gradually strengthened by steps of 50 €cents (= 0.5 €). Finally, the diet fulfilling all the imposed constraints at the lowest cost achievable (i.e., a solution was not feasible at a lower cost constraint) was also obtained.

Analysis of model robustness. Two models were developed that differed only in their objective function. First, departure from the average amount of energy contributed by food subgroups was minimized instead of departure from the average quantity of foods. Second, the total cost of the diet expressed in €cents was chosen as the objective function and minimized. These additional analyses were carried out to assess the robustness of the results and conclusions to the objective function chosen. Finally, models were also rerun that did not exclude rarely consumed foods, to examine model sensitivity this constraint.

Terminology. The term "mean population diet" refers to mean intakes of foods (in g/d) estimated for the ≥18-y-old men and women in the cross-sectional survey described above. The term "LP diets" refers to all diets generated using LP modeling. The term "lowest cost LP diets" refers to LP diets obtained when the cost constraint was set at the lowest level achievable.

RESULTS

Impact of a cost constraint on the cost contributed by food groups

In the mean population diets, the most expensive food group was meat/fish/eggs (representing 44% and 41% of the total diet cost, in men and women, respectively) followed by fruit and vegetables (representing 25% and 30% of the total diet cost in both men and women) (**Fig. 1**A). Those of moderate cost were cereals and dairy products (each food group represents <15% of the total diet cost regardless of gender). Added fats and sweets were the lowest cost food groups (representing <3% of the total diet cost regardless of gender). When no cost constraint was introduced, the LP diet was very similar to the mean population diet for both genders. Notably without a cost constraint, the total costs of the LP diets were 5.31 €/d and 4.31 €/d for men and women, respectively, which is similar to the cost of the observed mean population diet (i.e., 5.35 €/d and 4.41 €/d for men and women, respectively). Adding and strengthening a cost constraint resulted in a progressive and important decrease in the absolute cost of both the meat/fish/eggs and fruit and vegetables food groups for both genders and a slight cost increase for cereals, but primarily for men. In contrast, it had little impact on the absolute cost of other food groups, except for dairy products, which also decreased but only in the diets costing ≤3.0 €/d for men and ≤2.5 €/d for women. The lowest cost LP diets cost 2.52 €/d and 1.78 €/d for men and women, respectively. In these diets, cereals became the most expensive food group and meat/fish/eggs remained expensive relative to other food groups, despite an important decrease in their absolute expense.

Impact of a cost constraint on the energy contributed by food groups and subgroups

In the mean population diets, the largest proportion of total energy was contributed by cereals, followed by meat/fish/eggs, which again was similar to the LP diet obtained when no cost constraint was introduced (Fig. 1B). Strengthening the cost constraint resulted in an increase in the percentage of energy from cereals, added fats and sweets and a decrease in energy from fruit and vegetables and meat/fish/eggs. The energy con-

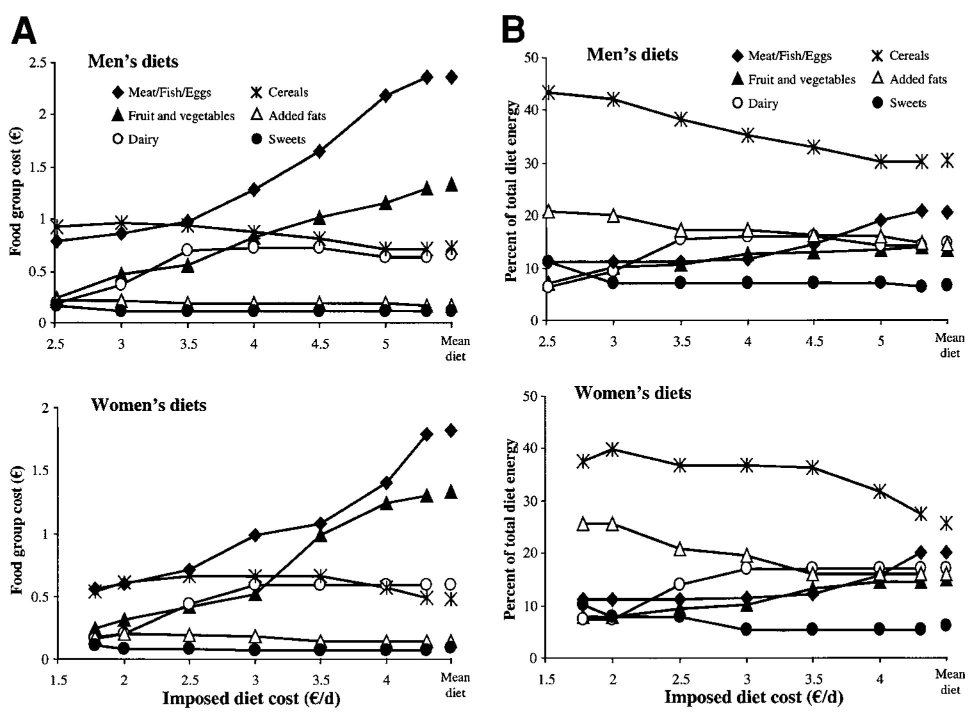

FIGURE 1 Impact of a cost constraint on the cost (1*A*) and the energy (1*B*) contributed by different food groups in the linear programming (LP) diets in comparison with the mean diet observed in population. The energy content of LP diets was equivalent to the mean energy intake observed in the population: 9.8 MJ/d (2347 kcal/d) for men and 7.3 MJ/d (1748 kcal/d) for women. They were minimized on total departure from the mean diet observed in the populations of men and women. A maximal cost constraint was introduced and gradually decreased by steps of 0.5 €. Finally, the cost constraint was set to the minimal value achievable, that is, 2.52 €/d and 1.78 €/d in men and women, respectively.

tributed by dairy products also decreased but only in the LP diets costing ≤3.0 €/d for men and ≤2.5 €/d for women. In the lowest cost LP diets, cereals remained the main source of energy. However, compared with the mean population diet, the relative contributions of added fats and meat/fish/eggs were reversed in the lowest cost LP diets (e.g., from 14% to 21% for added fats and from 20% to 11% for meat/fish/eggs in men). Strengthening the cost constraint had a differential impact on subgroups within each food group. In both men (**Table 1**) and women (**Table 2**), the diminution in energy contributed by fruit and vegetables in the LP diets was mainly the result of a decrease in vegetables and fresh fruit, whereas there was an increase from nuts/dried fruit. Likewise the decline in energy contributed by meat/fish/eggs was primarily accounted for by the diminution in energy from meat and fish, whereas the contribution from processed meat increased. Finally the diminution in energy contributed by the dairy product group in the LP diets was mainly the result of a decrease in the contribution from cheese and other dairy products, whereas that of milk increased.

Impact of a cost constraint on the nutrient content of the diets

In both men (**Table 3**) and women (**Table 4**), decreasing the cost of the LP diets resulted in a progressive increase in the proportion of energy from fats and carbohydrates, including sugars. This was compensated for by a decrease in the protein content of the LP diets, although these remained higher than the safe Population Reference Intakes (PRI) values for protein (36), even in the lowest cost LP diets. The mean population diets exceeded the PRI for all nutrients for men and for all nutrients except iron, selenium, iodine and potassium for women. For most micronutrients, strengthening the cost constraint resulted in a progressive decrease in nutrient density in the LP diets. In the diets costing ≤3.0 €/d for men and ≤2.5 €/d for women, the level of some nutrients [i.e., calcium, iron (women only), magnesium, copper (women only), zinc, selenium, iodine, potassium, vitamin C (women only), thiamin, riboflavin, vitamin B-6 and folate (women only)] was reduced to levels below or further below the PRI. Notably the women's diets costing ≤3.0 € had a particularly low iron content:

TABLE 1

Impact of a cost constraint on the energy contributed by different food groups and subgroups in LP diets designed for men in comparison with the mean diet observed in the population

		Mean diet for men	LP diets for men[1]						
Diet cost, *€/d*		5.35	5.31	5.00	4.50	4.00	3.50	3.00	2.52
	Imposed limits[2]	*Energy contributed by food groups and subgroups*[3]							
	kJ/d	*kJ/d*							
Fruit and vegetables	704–2135	1322	1365	1325	1278	1239	1055	1001	704
Vegetables	42–386	187	170	130	83	42*	42*	42*	42*
Fresh fruits	0–907	279	279	279	279	279	95	42	0*
Nuts, dried fruits	0–700	115	97	97	97	97	97	97	350
Processed fruits	0–523	113	113	113	113	113	113	113	0*
Potatoes	69–1128	489	567	567	567	567	567	567	311
Roots	0–180	52	52	52	52	52	52	52	0*
Legumes	0–291	87	87	87	87	87	87	87	0*
Meat, fish, eggs	1099–3188	2011	2039	1865	1433	1155	1109	1099*	1099*
Meat	474–2417	1324	1353	1179	747	474*	474*	474*	474*
Fish	0–468	193	193	193	193	188	142	32	0
Eggs	0–425	155	155	155	155	155	155	155	210
Offals	0–132	35	35	35	35	35	35	35	16
Processed meat	0–1367	303	303	303	303	303	303	403	400
Dairy products	613–2449	1441	1392	1392	1566	1566	1516	922	613*
Milk	0–1027	278	255	255	255	255	255	255	526
Cheese	0–1768	789	789	789	963	963	913	436	0*
Other dairy products	0–1240	374	348	348	348	348	348	231	87
Cereals	1437–4919	2979	2963	2963	3253	3473	3752	4133	4275
Rice, pasta, bread	823–4139	2249	2272	2272	2318	2318	2318	2318	2666
Other cereals	0–2672	730	691	691	935	1154	1434	1815	1609
Added fats	643–2311	1422	1450	1572	1586	1685	1685	1962	2045
Vegetable fats	188–1881	902	902	902	916	1015	1015	1293	1293
Animal fats	0–1362	520	548	670	670	670	670	670	752
Sweets	86–1481	648	614	706	706	706	706	706	1088
Without chocolate	0–1456	470	437	529	529	529	529	529	744
With chocolate	0–797	177	177	177	177	177	177	177	344

[1] All LP diets were isoenergetic and equivalent to the mean energy intake observed in men: 9.8 MJ/d (2347 Kcal/d). They were minimized on total departure from the mean diet observed in a population of men. Then a cost constraint was introduced and gradually decreased in steps of 0.5 €. Finally, the cost constraint was set to the minimal value achievable: 2.52 €/d.

[2] All LP diets fulfilled minimal and maximal constraints on the quantity of energy contributed by each food group and subgroup in the diet, which corresponded to the 10th and the 90th percentiles and to the 5th and the 95th percentiles, respectively, of the population distribution for men.

[3] Energy values that were equivalent to the minimal or maximal limits imposed in the models are indicated by an asterisk.

TABLE 2

Impact of a cost constraint on the energy contributed by different food groups and subgroups in LP diets designed for women in comparison with the mean diet observed in the population

		Mean diet for women	LP diets for women[1]						
Diet cost, €/d		4.41	4.31	4.00	3.50	3.00	2.50	2.00	1.78
	Imposed limits[2]	*Energy contributed by food groups and subgroups*[3]							
	kJ/d	*kJ/d*							
Fruit and vegetables	576–1703	1103	1055	1055	970	735	678	576*	576*
Vegetables	59–396	199	176	176	91	59*	59*	59*	59*
Fresh fruits	0–832	294	294	294	294	91	34	0*	0*
Nuts, dried fruits	0–447	77	52	52	52	52	52	106	350
Processed fruits	0–523	94	94	94	94	94	94	28	0*
Potatoes	0–798	320	320	320	320	320	320	320	167
Roots	0–172	51	51	51	51	51	51	0*	0*
Legumes	0–269	67	67	67	67	67	67	62	0*
Meat, fish, eggs	823–2200	1466	1458	1142	882	838	823*	823*	823*
Meat	337–1668	981	981	665	405	361	337*	337*	337*
Fish	0–468	179	171	171	171	171	112	22	0*
Eggs	0–327	140	140	140	140	140	210	210	103
Offals	0–132	29	29	29	29	29	29	29	0*
Processed meat	0–676	137	137	137	137	137	137	227	384
Dairy products	535–2125	1240	1240	1240	1240	1240	1030	535*	535*
Milk	0–805	232	232	232	232	232	232	250	472
Cheese	0–1583	574	574	574	574	574	513	0*	0*
Other dairy products	0–1081	433	433	433	433	433	285	285	63
Cereals	794–3332	1885	2000	2316	2660	2683	2683	2919	2753
Rice, pasta, bread	257–2644	1333	1485	1801	2145	2168	2168	2165	1999
Other cereals	0–2043	552	515	515	515	515	515	754	754
Added fats	507–1883	1168	1168	1168	1168	1425	1522	1883*	1883*
Vegetable fats	150–1577	735	735	735	735	735	832	1293	1293
Animal fats	0–1083	433	433	433	433	690	690	590	590
Sweets	0–983	453	394	394	394	394	578	578	744
Without chocolate	0–993	330	285	285	285	285	469	469	744
With chocolate	0–548	124	109	109	109	109	109	109	0*

[1] All LP diets were isoenergetic and equivalent to the mean energy intake observed in women: 7.3 MJ/d (1748 Kcal/d). They were minimized on total departure from the mean diet observed in a population of women. Then, a cost constraint was introduced and gradually decreased by steps of 0.5 €. Finally, the cost constraint was set to the minimal value achievable: 1.78 €/d.

[2] All LP diets fulfilled minimal and maximal constraints on the quantity of energy contributed by each food group and subgroup in the diet, which corresponded to the 10th and the 90th percentiles and to the 5th and the 95th percentiles, respectively, of the population distribution for women.

[3] Energy values that were equivalent to the minimal or maximal limits imposed in the models are indicated by an asterisk.

<50% of the PRI. In the lowest cost LP diet for women, calcium, zinc, potassium, folate and vitamins B-6 and D were reduced to <50% of the mean intakes observed in the French female population. Moreover the vitamin C and β-carotene contents of the lowest cost LP diets represented <25% and <10% of the mean observed intakes for both men and women, respectively. Of all the dietary constituents examined, only vitamins E and A, retinol and polyunsaturated fatty acids (PUFA) were relatively unaffected by the cost constraint. Indeed retinol and PUFA instead increased when diet costs were decreased; the former contributed to the relatively consistent vitamin A levels observed across LP diets because it compensated for the decreased β-carotene content observed with decreasing costs.

Model robustness

Analyses confirmed that the results were not sensitive to the objective function chosen. Regardless of the objective function, that is, minimization on foods (TDMI) or food subgroups, the relative contributions of food subgroups selected for men and women in response to the cost constraint were similar (data not shown). Likewise the diets directly minimized on cost were remarkably similar to those minimized on TDMI when the cost constraint was most severe (i.e., ≤2.52 €/d and ≤1.78 €/d for men and women, respectively) except that the food group of "other dairy products" was not selected in the diets minimized on cost (data not shown). This again confirms the robustness of the analysis to the objective function chosen. Likewise removing the constraint that excluded rarely consumed foods did not modify the conclusions. Finally the energy contributed by food groups and subgroups in the lowest cost LP diets were closely examined to assess whether removing the food group constraints would modify the conclusions. In the lowest cost LP diets, the energy contributed by meat, fish, dairy products and fruits and vegetables were at the lowest constraint limits; for added fats (women only), at the upper constraint limit. In other words the conclusion that a cost constraint encourages a reduction in the energy contributed by meat, fish, dairy products and fruits and vegetables and an increase in the energy contributed by added fats would even be reinforced by removing the food group constraints in the models.

TABLE 3

Impact of a cost constraint on the nutrient content of LP diets designed for men compared with the mean diet observed in the population and the PRI[1]

		Mean diet for men	LP diets for men[2]						
Diet cost, *€/d*	PRI	5.35	5.31	5.00	4.50	4.00	3.50	3.00	2.52
Macronutrients									
Carbohydrate, *% total diet energy*	—	42.8	42.7	43.3	44.6	45.3	44.7	45.9	47.1
Sugars, *% total diet energy*	—	6.8	6.3	7.3	7.8	7.9	8.0	8.3	8.3
Fatty acids, *% total diet energy*	—	39.9	40.2	40.3	40.1	40.5	42.0	42.8	42.2
SFA, *% total diet energy*	—	16.2	16.3	16.5	16.6	16.4	17.1	17.0	15.4
PUFA, *g/d*	7.5	14.7	14.5	14.5	14.6	15.4	15.5	18.1	19.9
Protein, *g/d*	56	101.3	100.6	96.2	90.2	83.3	78.2	66.3	63.2
Minerals[3]									
Calcium, *mg/d*	700	1052	1009	991	1056	1037	1011	678*	578*
Magnesium, *mg/d*	255	288	282	272	263	251*	239*	222*	232*
Iron, *mg/d*	9	13.6	13.4	12.5	11.1	9.9	9.5	9.9	10.0
Copper, *mg/d*	1.1	1.5	1.5	1.5	1.4	1.4	1.3	1.2	1.3
Zinc, *mg/d*	9.5	13.8	13.7	12.8	11.0	9.6	9.5	7.7*	6.9*
Selenium, *µg/d*	55	66	66	64	63	60	56	51*	50*
Iodine, *µg/d*	130	134	131	129	133	133	129*	106*	118*
Potassium, *mg/d*	3100	3388	3403	3232	2987*	2741*	2496*	2229*	1876*
Vitamins[3]									
Vitamin D, *µg/d*	—	3.4	3.4	3.5	3.7	3.9	4.0	2.3	2.1
Thiamin, *mg/d*	1.1	1.2	1.2	1.1	1.1	1.0*	0.9*	0.8*	0.8*
Riboflavin, *mg/d*	1.6	2.0	1.9	1.9	1.8	1.7	1.6	1.3*	1.4*
Niacin, *mg/d*	18	40	39	37	33	30	28	25	24
Vitamin C, *mg/d*	45	114	113	105	97	86	78	54	24*
Vitamin E, *mg/d*	4	9.6	9.5	9.3	9.0	9.4	9.4	10.0	10.6
Vitamin B-6, *mg/d*	1.5	1.9	1.9	1.8	1.7	1.6	1.5	1.3*	0.9*
Folate, *µg/d*	200	415	405	376	346	272	248	232	210
Vitamin B-12, *µg/d*	1.4	12.4	12.4	12.3	12.5	12.3	11.6	10.9	10.4
Vitamin A, *µg retinol Eq/d*	700	2169	2086	1919	1736	1750	1728	1943	1827
β-Carotene, *µg retinol Eq/d*	—	1020	933	735	504	499	462	458	91
Retinol, *µg/d*	—	1148	1154	1183	1232	1251	1266	1484	1736

1 PRI, Population Reference Intakes (36); SFA, saturated fatty acids; PUFA, polyunsaturated fatty acids.

2 All LP diets were isoenergetic and equivalent to the mean energy intake observed in men: 9.8 MJ/d (2347 Kcal/d). They were minimized on total departure from the mean diet observed in a population of men. A cost constraint was then introduced and gradually decreased by steps of 0.5 €. Finally, the cost constraint was set to the minimal value achievable: 2.52 €/d.

3 Nutrient contents lower than the PRI are indicated by an asterisk.

DISCUSSION

The present results showed that a simple cost constraint influences food selection in ways that decrease nutrient densities. Altogether they suggest that the unhealthy eating patterns and nutritional inadequacy often observed in persons of low SES (1–11) may be the result of economic constraints.

In the present study, forcing the cost of the LP diets to decrease resulted in a diminution in the contribution of meat, fish, cheese and fruits and vegetables combined with an increase in cereals, processed meat, milk and added fats. Such a food pattern is strikingly similar to those observed in low SES groups in food consumption surveys conducted in industrialized countries (2–7,9,10), including France (8). Indeed, meat, fish and fruits and vegetables are the most expensive food items in an average western diet (22). Another noteworthy finding in the present study was that at least 2.52 €/d for men and 1.78 €/d for women were needed to fulfill the mean energy needs for populations consuming diets similar to usual food consumption patterns observed in France (i.e., a solution was not possible at lower costs). This price is remarkably comparable with average expenditures on food among people with an income below the poverty level living in France, that is, 2.5 €/d (37). Our results therefore suggest that this segment of the population is facing very severe food choice restrictions because of economic constraints.

Except for some fat-soluble nutrients such as vitamin E, retinol and PUFA, a diminution in diet cost was associated with a decline in nutrient density. This decline was particularly noteworthy for vitamin C and *β*-carotene, suggesting that intakes of these nutrients are particularly sensitive to poverty. These results were consistent with population-based surveys that have reported low vitamin C and *β*-carotene status (38,39) and intakes (2–5,40) and high intakes of retinol (4,5) in low SES groups. Also in accordance with our results, lower intakes of folate (2) and potassium (41) have been reported in low compared with high SES groups. The increase in refined cereals and added fats and the decrease in fruits and vegetables observed with strengthening of the cost constraint were not strictly paralleled by an increase in total fat, notably because fat from meat decreased before fat from added fats increased. Consequently the fat content of LP diets was markedly above the population mean only in the diets costing ≤3.5 €/d for men and ≤2.0 €/d for women. This complex relationship between fat and diet cost may explain some of the discrepancies reported in estimated fat intakes of persons of low SES (3,4,6,9,10,40–42).

The limitations of the present study must also be noted.

TABLE 4

Impact of a cost constraint on the nutrient content of LP diets designed for women compared with the mean diet observed in the population and the PRI

		Mean diet in women	LP diets for women[2]						
Diet cost, €/d	PRI	4.41	4.31	4.00	3.50	3.00	2.50	2.00	1.78
Macronutrients									
Carbohydrate, % total diet energy	—	41.0	41.1	44.8	47.8	45.1	46.1	46.4	44.9
Sugars, % total diet energy	—	6.4	5.5	5.5	5.5	5.5	8.0	8.3	7.1
Fat, % total diet energy	—	41.0	40.8	38.2	36.2	39.4	40.5	42.3	44.5
SFA, % total diet energy	—	16.5	16.4	15.2	14.3	16.2	16.0	14.8	14.7
PUFA, g/d	5.5	11.4	11.4	11.3	11.3	11.4	12.0	16.3	16.9
Protein, g/d	47	78.7	79.0	74.3	70.1	67.5	58.6	49.4	47.2
Minerals[3]									
Calcium, mg/d	700	937	922	922	889	849	669*	439*	470*
Magnesium, mg/d	204	227	223	224	215	200	179*	170*	166*
Iron, mg/d	16	10.6*	10.3*	9.7*	8.6*	7.5*	7.3*	7.3*	7.3*
Copper, mg/d	1.1	1.2	1.2	1.2	1.1	1.0*	0.9*	0.8*	0.8*
Zinc, mg/d	7	10.5	10.5	9.1	7.9	7.5	6.8*	5.1*	4.8*
Selenium, μg/d	55	49*	49*	49*	49*	48*	45*	46*	38*
Iodine, μg/d	130	112*	112*	114*	114*	112*	98*	84*	88*
Potassium, mg/d	3100	2870*	2772*	2696*	2404*	2054*	1727*	1475*	1303*
Vitamins[3]									
Vitamin D, μg/d	—	3.0	3.0	3.0	3.0	3.1	3.0	1.5	1.1
Thiamin, mg/d	0.9	1.0	1.0	1.0	0.9	0.8*	0.6*	0.6*	0.5*
Riboflavin, mg/d	1.3	1.7	1.7	1.6	1.5	1.4	1.2*	1.0*	1.0*
Niacin, mg/d	14	31	31	28	26	24	21	19	18
Vitamin C, mg/d	45	107	103	103	88	69	43*	27*	22*
Vitamin E, mg/d	3	8.1	7.9	7.8	7.3	7.3	7.6	8.9	8.4
Vitamin B-6, mg/d	1.1	1.5	1.5	1.4	1.2	1.2	1.0*	0.7*	0.6*
Folate, μg/d	200	374	360	364	311	214	199*	176*	174*
Vitamin B-12, μg/d	1.4	10.4	10.4	10.3	10.2	10.2	11.3	10.8	6.2
Vitamin A, μg retinol eQ/d	600	1855	1732	1732	1311	1397	1398	1144	1548
β-Carotene, μg retinol eQ/d	—	1043	922	922	500	524	520	110	106
Retinol, μg/d	—	812	811	811	811	873	878	1034	1443

[1] PRI, Population Reference Intakes (36); SFA, saturated fatty acids; PUFA, polyunsaturated fatty acids.
[2] All LP diets were isoenergetic and equivalent to the mean energy intake observed in women: 7.3 MJ/d (1748 Kcal/d). They were minimized on total departure from the mean diet observed in a population of women. A maximal cost constraint was then introduced and gradually decreased by steps of 0.5 €. Finally, the cost constraint was set to the minimal value achievable: 1.78 €/d.
[3] Nutrient contents lower than the PRI are indicated by an asterisk.

First, the price of a given food item may vary according to season and place of purchase (32). However, it is the hierarchy of prices, rather than their absolute values, that will have an impact on the results in the present analysis. In addition, the food price and dietary data used in the present study correspond to different time periods (i.e., 2000 and 1988). Some changes in dietary patterns may have occurred since 1988. A recent report suggests that these changes, however, are minor: notably, fat intake remains high in France, providing ~40% of the nonalcoholic energy intake for both genders (43). In addition, the estimated cost of the mean diet observed in the population (i.e., 5.35 €/d and 4.41 €/d for men and women, respectively) was remarkably similar to the current mean national expenditure for food at home, that is, 4.9 €/d (44). Second, assumptions were made that *i*) an individual facing economic constraints will minimize the difference between his or her diet and mean population food intakes when choosing foods and *ii*) energy intake will be the only nutritional constraint respected under these conditions. These assumptions were based on observations that low SES or food-insufficient individuals *i*) maintain familiar dietary patterns (34) and *ii*) reduce food quality before food quantity (35). Third, the mathematical function developed to minimize departure from the mean diet observed in the population gives equal importance to all foods. In reality, there might be a disproportionate decline in the consumption of less-favored foods to continue consuming favorite foods, as suggested by experimental data (45). Fourth, the reference diet was chosen because it represents an average French diet (31), and not because it fulfills criteria for a healthy diet; notably it has a high fat and saturated fatty acid content. It does, however, exceed the PRI for most nutrients (Tables 3 and 4), minimizing risks of inadequate nutrient intake for individuals who consume it. It also reflects our objective to model expected choices an individual would make in cost-constrained conditions.

The present results suggest that the budget for food directly influences food selection and therefore diet quality. This is in agreement with evidence from other studies showing that food choices change when the ratio of cost to palatability of food is artificially modified in an experimental setting (45) and that nutrition education combined with an economic intervention was more effective than nutrition alone in increasing fruit and vegetable consumption (46). Likewise economic analysis showed that meats, fresh fruits and vegetables have high income elasticities (i.e., the percentage changes in the demand for a food resulting from a 1% change in income), whereas staples have low income elasticities (47). Therefore several studies, using vastly different methodology, have shown the important role of economic factors in food selection. The unique contribution from the present study is that it shows that a cost constraint on the food budget, independent of other factors, can result in the selection of diet with a low micronutrient density. Obviously cultural factors such as social/family support nutrition knowledge or cooking skills might attenuate the deleterious impact of poverty on nutrition and health.

Our results suggest that, when food selection is constrained by economic considerations, healthy eating patterns will be necessarily compromised, which will result in nutritional inadequacy. This is of significant public health interest because it suggests that nutrition education alone may prove ineffective unless it is combined with economic measures aimed at improving the affordability of a healthy diet.

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