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Fuzzy sets and fuzzy decision making in nutrition

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Objective: This paper demonstrates that a nutrient intake can be described in a differentiated way and can be evaluated by employing fuzzy decision making. It also examines whether fuzzy decision making can simplify nutrition education by small individual improvements in food selection behaviour.

Results: The recommendations for nutrient intakes are presented as fuzzy sets, so that the intake of each nutrient can be evaluated by an objective fuzzy value. The evaluation of the harmonic minimum allows, for the first time, that the fuzzy value of an individual nutrient can be stated as a total value. On the basis of individual nutrition assessment, fuzzy logic in connection with fuzzy decision making, allows optimization of meals considering individual food preferences. This makes it possible in nutrition counselling to improve the nutrient intake markedly with relative small changes in food choice.

Conclusion: Fuzzy decision making can simplify and optimize nutrition education.

Descriptors: Recommended dietary allowances; fuzzy logic; fuzzy sets; fuzzy decision making; optimization; nutrition education.

Introduction

Many countries and international agencies have published recommendations for the intake of nutrients. The general policy is to recommend an intake that covers the needs of all or almost all members of a certain population group. This value is often derived by taking the average requirement (AR) of a specific group and addding two standard deviations (s.d.). On this basis, the calculated population reference intake (PRI) is the intake that will meet the needs of 97.5% of all healthy people in the group. The AR minus 2 s.d. gives the lowest threshold intake (LTI). This is the intake below which almost all individuals will be unlikely to maintain metabolic integrity. The LTIs are often set on the prudent side, being not those intakes below which deficiency is almost certain, but rather those intakes below which there may be a cause for concern for a substantial section of the population. For most nutrients, the PRI can be exceeded several fold without causing adverse effects and although any additional benefits are unlikely for most nutrients, there usually is no harm in consuming amounts that are much higher than the PRI. For some nutrients, however, undesirable effects can occur at amounts even relatively close to the PRI. Neither the safe upper limits nor the toxic area of intake are normally listed in official committees publications. However, occasionally some comments are to be found about excessive intakes and toxicity.

For most nutrients LTI, AR and PRI are given as single numbers. But for some nutrients the data are inadequate for making recommendations. For these nutrients an acceptable range of intakes is given, based on observations that individual consumptions within these limits apparently are satisfactory in that neither deficiency nor signs of excess are seen. These intervals and the values of LTI, AR and PRI do not represent the full reality, which is a continuous transition from critical low intake to adequate intake to excess or even toxic amounts.

In this paper the recommendations are not represented as fixed numbers but as fuzzy sets. These are curves describing the membership to the set 'optimal intake'. With the help of these sets, an evaluation of nutrient intake as well as an optimization of food in nutrition education seems to be possible.

Methods

Fuzzy sets

In general, the nutritional status assessment based on nutrient intake is evaluated by comparison of intake with the official recommendation for that person. However, this does not allow for evaluation of the degree of variation from the intended recommendation. Biologically there is a continuous transition form marginal to optimal intake to toxic intake.

Truswell (1992) presented a diagram (Figure 1), which shows the degree of health when varying the intake of one essential nutrient and holding the rest of the diet constant at an optimal level. There exists a very dangerous area of low intake, an area of deficiency diseases, a marginal area and a large optimal range. Here the health does not improve or deteriorate as the intake is changed; for most nutrients this is quite a wide range. There is therefore no single optimal intake. The recommended dietary intake or reference nutrient intake is intended to be at the top of the left hand slope in the diagram. On the other hand, there exists a marginal

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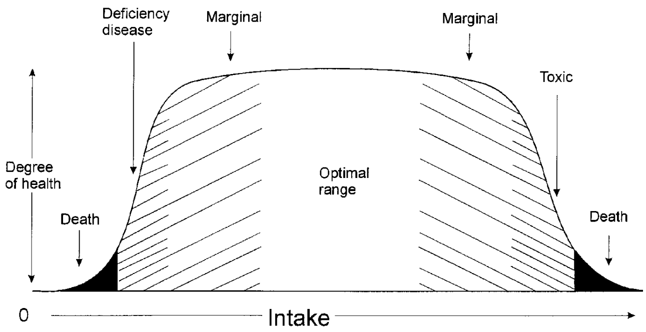

Figure 1 Degree of health when varying the intake of one nutrient and holding the rest of the diet constant.

area of high intake, a toxic area and, at the end again, a very dangerous area.

Truswell's diagram can also be interpreted as a curve describing the 'optimal intake'. It can be used to define a fuzzy set as shown in Figure 2. In the case of the fuzzy set optimal intake $\mu(x_i)$ is now called the membership function (Mayer *et al*, 1993) or grade of membership of the intake x_i in the fuzzy set A_i. The membership function can vary between 0 and 1. The value 0 represents the worst status possible, death. The value 1 represents the absolute optimum. The PRIs do not necessarily represent the optimum intake for every nutrient for either individuals or populations because that is not their purpose.

All values between 0 and 1 can be described verbally. In

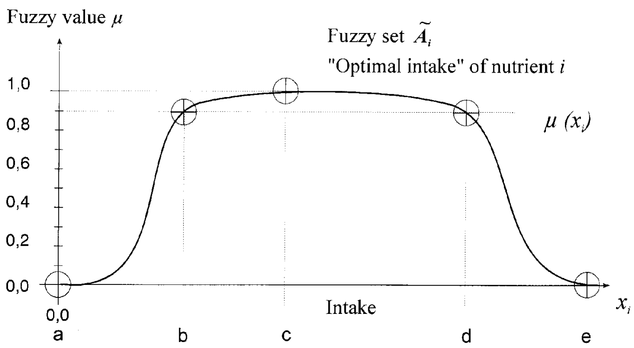

Figure 2 The fuzzy set 'optimal intake' of a nutrient.

fuzzy logic, linguistic variables (Zadeh, 1973 can be used for this purpose. These are variables whose values are not numbers but words or sentences in a natural language. The membership functions for several liguistic terms used in denoting the fuzzy set 'optimal intake' are shown in Figure 3. On the basis of these verbal interpretations fuzzy sets were developed for those nutrients for which German nutrition recommendations (DGE, 1992) exist and for which data are to be found in the German nutrition data base (BLS, 1995). The definition of the fuzzy sets is based on the German recommendations, but all sets are consistent with the European recommendations (SCF, 1993) and the US Recommended Dietary Allowances (RDA) (NRC, 1989).

For the construction of the fuzzy sets, five points are used (Figure 2):

(a) the fuzzy value for zero intake. For essential nutrients this value is 0, for semi-essential nutrients (for example dietary fibre) this fuzzy value lies between 0 and 1, for some other substances (cholestrol, alcohol, sucrose) the optimal status is reached at no intake. The fuzzy value is 1.
(b) safe minimum limit, corresponding to a fuzzy value of 0.9 (vertical line in the fuzzy set diagrams).
(c) optimal intake, corresponding to a fuzzy value of 1.
(d) safe upper limit, corresponding to a fuzzy value of 0.9 (vertical line in the fuzzy set diagrams).
(e) the toxic perilous area, corresponding to a fuzzy value of 0.

These points were fitted segment by segment by parabolas to get smooth curves. All fuzzy sets for the nutrients were plotted from zero intake to approximately three times the recommended intake for the nutrient. The fuzzy sets shown in Figures 4–9, are for men between 25 and 51 y of age with an average body size and a light level of physical activity.

Results and discussion

The fuzzy sets for most nutrients are shown in Figures 4–8. As examples for the definition of fuzzy sets, those for protein, fibre, water, fluoride and some further substances are discussed in detail.

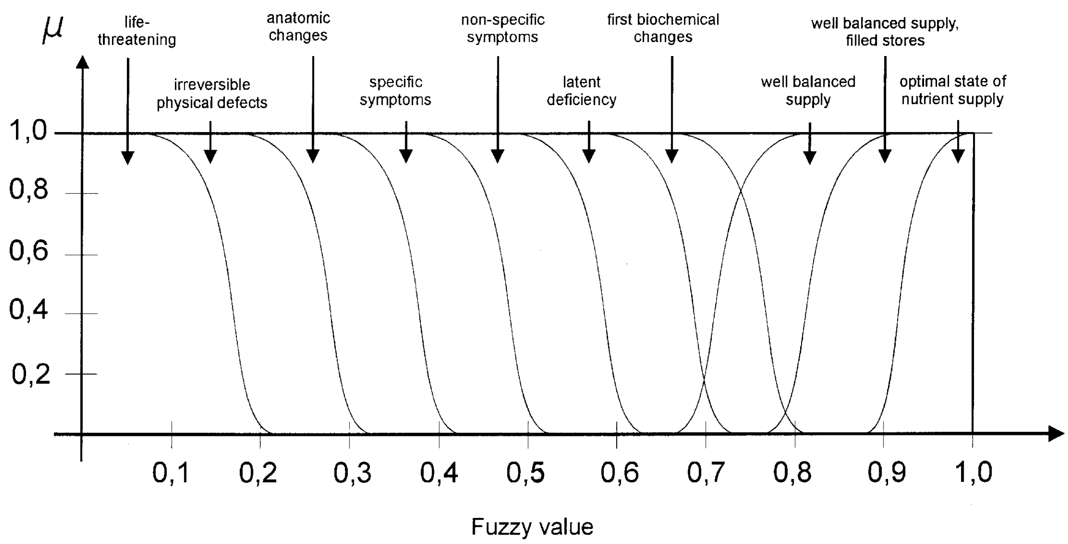

Figure 3 The membership function μ for some linguistic variables.

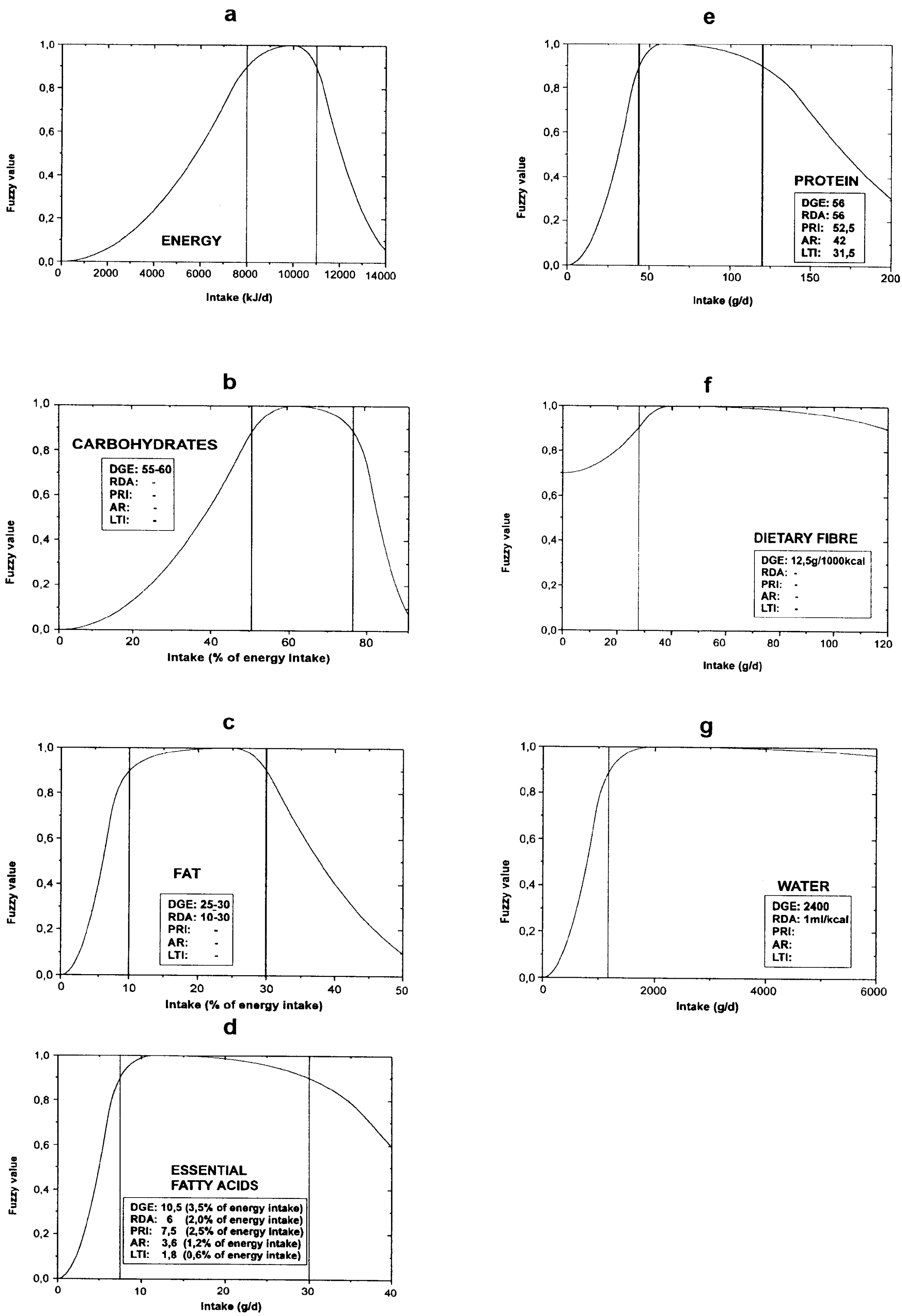

Figure 4 Energy, main nutrients, dietary fibre and water.

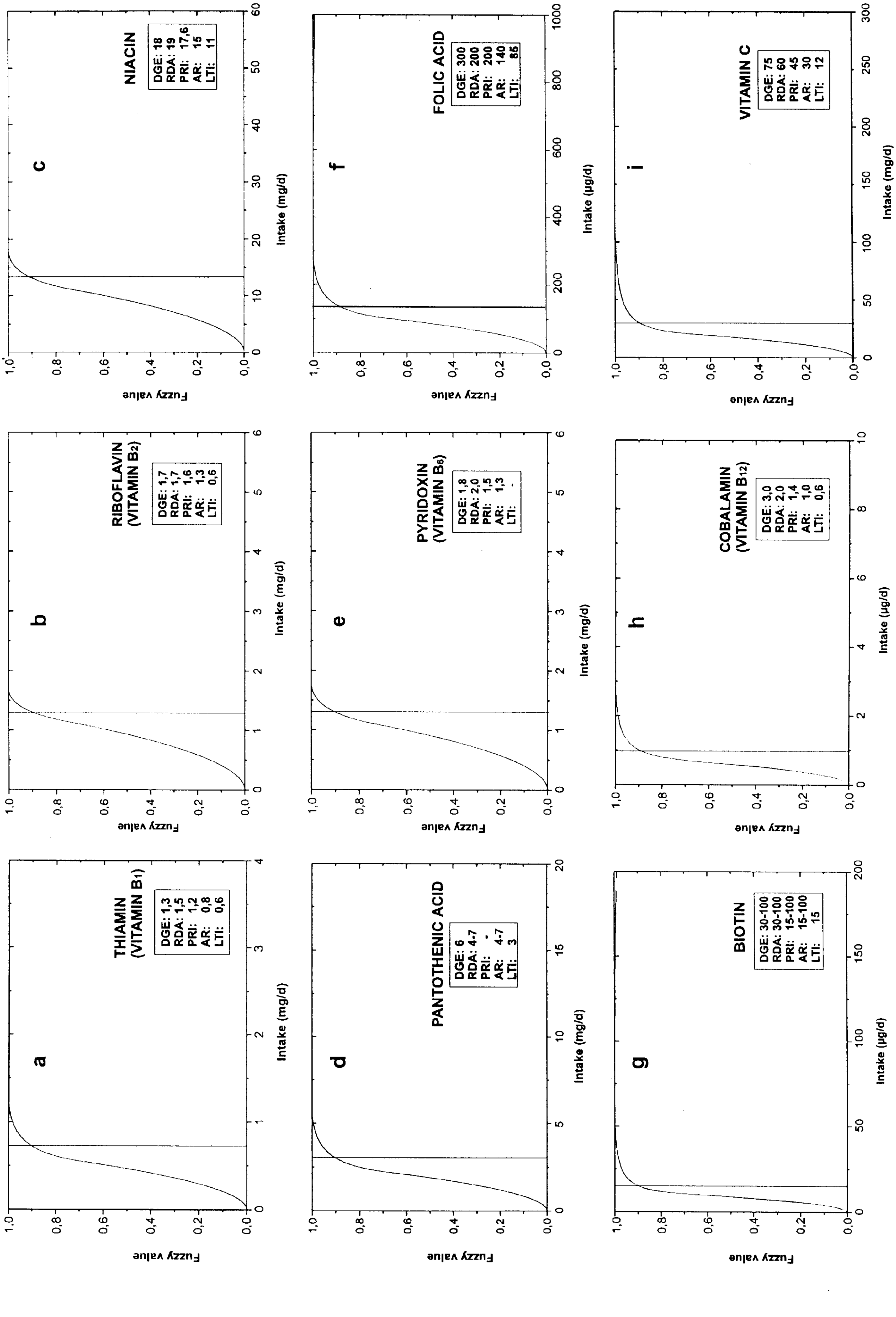

Figure 5 Water-soluble vitamins.

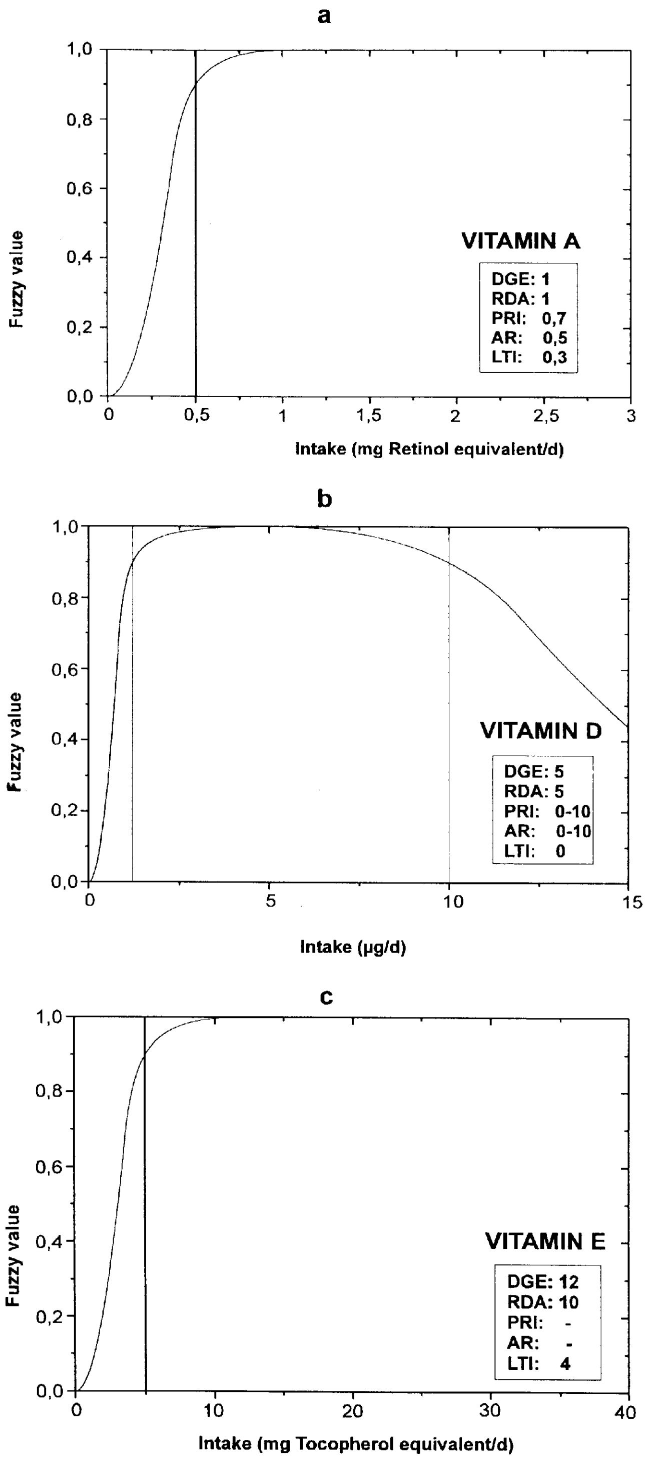

Figure 6 Lipid-soluble vitamins

To determine protein requirements, evidence from nitrogen balance studies were reviewed (Millward and Rivers, 1988; Millward *et al*, 1989). From these studies nearly all committees chose an average of 0.6 g/kg bodyweight/day as a reasonable minimum amount for adult men. The PRI is calculated by the SCF (1993) as 0.75 g/kg bodyweight/day by the DGE (1992) and by the NRC (1989) as 0.8 g/kg per day.

Because the system for disposal of excess nitrogen is efficient, protein intakes moderately above the requirement are believed to be safe. It has, however, been deemed prudent to maintain an upper limit of no more than twice the PRI for protein (NRC 1989). Allen *et al*, 1979 showed that there might be a potential for excess dietary protein to mobilize bone calcium and accelerate bone loss. The fuzzy set for protein shows a steep left slope and gradually decreases after its optimal value (Figure 4e).

Dietary fibre is the subject of considerable interest and extensive reviews (Kritchevsky, 1988; Lanza *et al*, 1987). In Germany, mean fibre intake is found to be approximately 20–25 g/d. Vegetarians and Africans have an intake of 50–100 g/d (Elmadfa and Leitzmann, 1990). The recommended dietary intake in Germany is a minimum of 30 g/d (DGE, 1992). A slightly greater intake would be better, but too much inhibits the absorption of other nutrients, especially minerals. Dietary fibre is not essential, therefore, the fuzzy set for dietary fibre (Figure 4f) starts with a fuzzy value of 0.7 for zero intake, corresponding to a verbal interpretation of some biochemical changes.

Although *water* is often excluded from lists of nutrients, this substance is an essential dietary component. The actual estimation of a water requirement is highly variable and quite complex. For practical purposes, 0.25 ml water/kJ of energy can be recommended as the water requirement for adults under average conditions (Hierholzer *et al*, 1991; DGE, 1992). However, there is so seldom a risk of water intoxication that the specified requirement for water is often increased to 0.36 ml/kJ. Toxicity results from the ingestion of water at a rate beyond the capacity of the kidneys to excrete the extra load, resulting in hypo-osmolarity. Such a condition is rarely observed in a normal healthy adult (NRC, 1989). The fuzzy set for water (Figure 4g) is therefore highly asymmetric, showing a steep slope on the left and a long area of optimal intake on the right.

The status of *fluoride* as an essential nutrient is controversial. This element has, however, been accepted as being beneficial to dental health (Schamschula and Barnes, 1981). Therefore, the fuzzy set for fluoride belongs to the semi-essential type and starts at 0.8 for zero intake (Figure 8f). SCF (1992) gave no recommendations for fluoride, because there apparently is not a specific physiological requirement for this element. The NRC (1989) set an estimated range of safe and adequate intakes of fluoride for adults at 1.5 to 4 mg/d, which is identical with the DGE (1992) recommendation.

Fluoride is toxic when consumed in excessive amounts. Acute toxicity and death have been reported in adults exposed to intakes of more than 500 mg/d (Wallbott, 1981). In addition to the fuzzy sets for essential nutrients, fuzzy sets for some *other dietary substances* can be defined, for example cholestrol, alcohol and sucrose. As they are not essential the membership functions for zero intake do not start at the zero point; as they are generally not considered beneficial to health, they start with a fuzzy value of 1 (Figure 9). This means the optimum is reached with zero intake which classifies such substances as more or less critical.

The NRC (1989) and the DGE (1992) recommend that dietary *cholesterol* should be less than 300 mg/d. For construction of the fuzzy set for cholesterol this value is taken as a safe upper limit (Figure 9a).

No upper limits for *alcohol* (Figure 9b) are given by NRC (1992) or SCF (1992) . The DGE (1992) has drawn attention to alcohol problems without giving recommendations. Some studies (Teschke and Liebes, 1981; Trojan, 1980) indicate that an upper limit of 10 g/d is appropriate.

Sugars, including *sucrose* (Figure 9c), in foods, provide a substrate for microorganisms in the mouth that are responsible for tooth decay. An adequate intake of

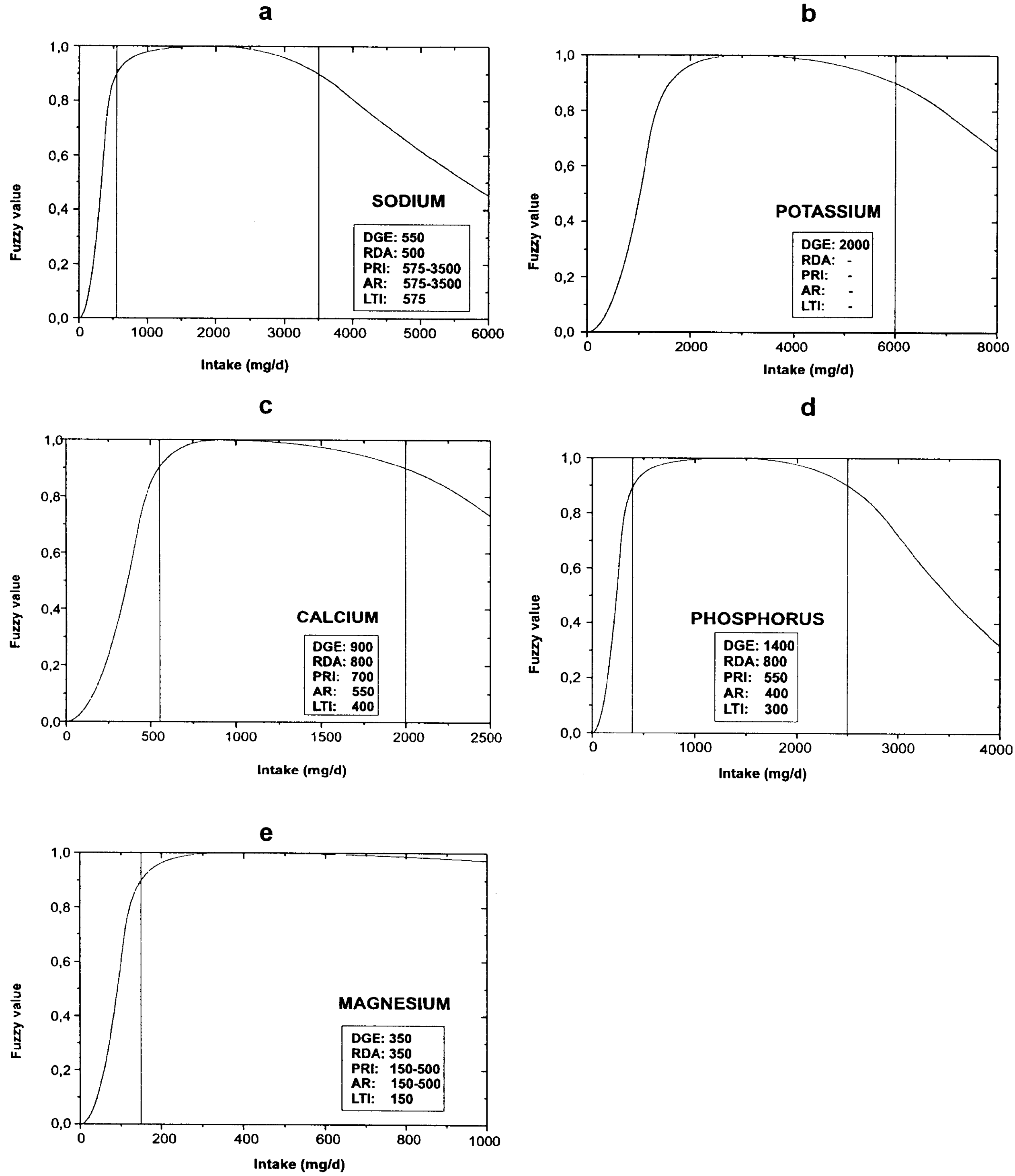

Figure 7 Macrominerals.

fluoride and a limited consumption of dietary sugars inhibit tooth decay. Limiting intake of sucrose to a maximum of 10% of energy intake is recommended by the DGE (1992).

The Prerow value

In practical nutrition education, single nutrients can not be optimized without considering other nutrients. For example, if there is too little dietary fibre and too much energy in the diet, adding wholemeal bread gives more dietary fibre, but also more energy, too. To solve this problem and to represent the logic 'and' (because the goal is to reach good intakes for both dietary fibre and energy) compromises have to be made. In fuzzy logic this is done with special operators.

The operator used by Wirsam (1994) was further developed and called the 'Harmonic Minimum' which is the minimum operator corrected by the harmonic mean for all other fuzzy values (x_i). Its application to the fuzzy sets of all nutrients for which German nutrition recommendations exist and for which data are to be found in the German

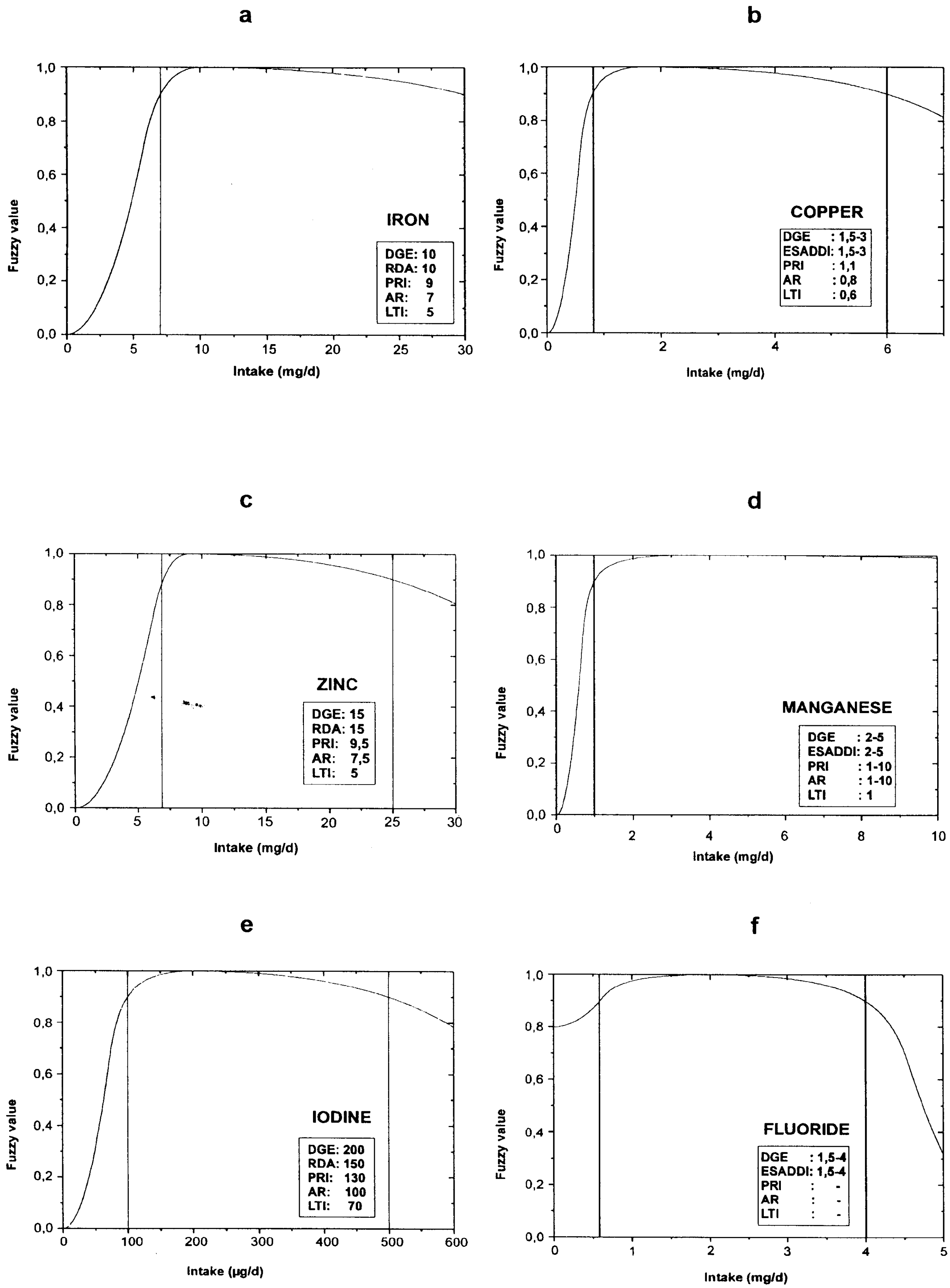

Figure 8 Microminerals.

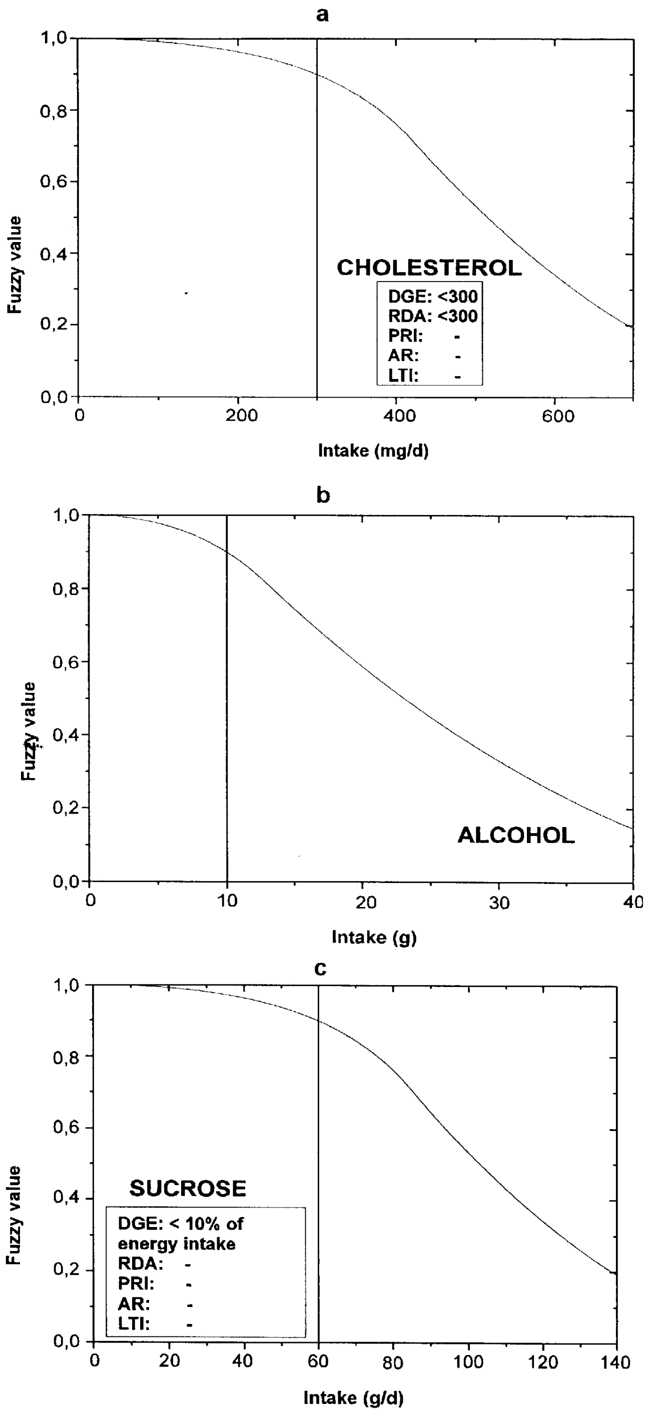

Figure 9 Further substances.

nutrient data bank (BLS 1995), gives the so called 'Prerow value' (PV) (Wirsam, 1994)

$$PV := \min(x_i) \cdot \frac{1}{\frac{1}{n-1} \sum_{i \neq \min}^{n} \frac{1}{x_i}}$$

The 'Prerow value' so defined is a measure of how closely the German nutrition recommendations are reached. In relation to other operators (arithmetic, geometric mean) this operator is close to the minimum, which represents the logical 'and'. In comparison with the minimum-operator it is sensitive for all other fuzzy values. If membership $=0$ for one nutrient ($=$death) the Prerow value itself is 0. In large models the nutrient with the lowest value has the strongest influence on the Prerow value.

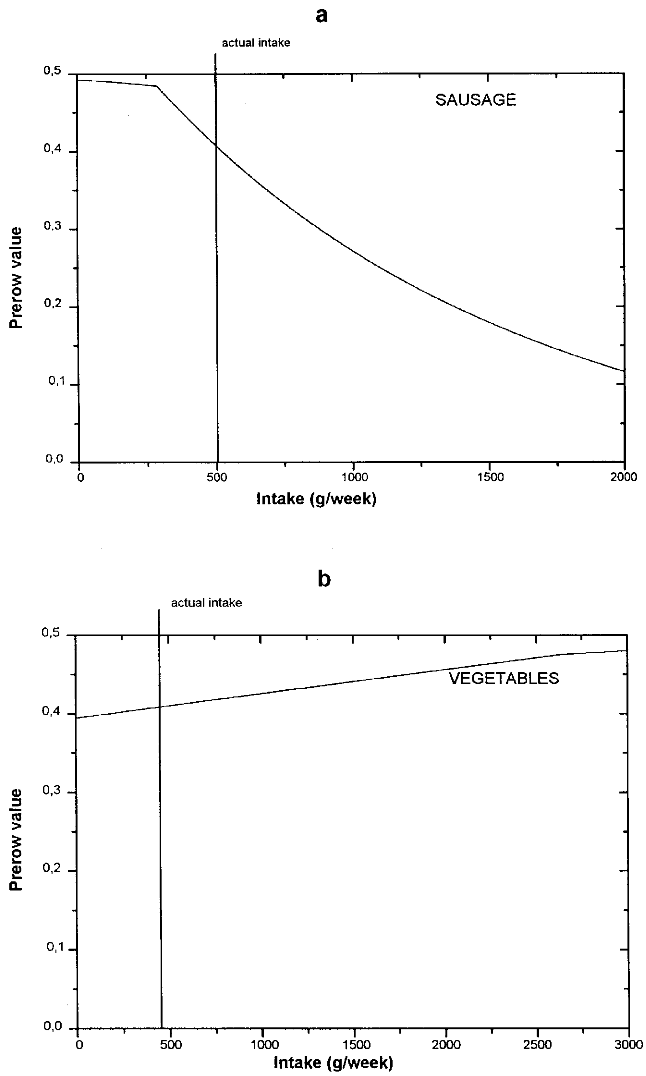

Figure 10 Variation of the Prerow value when varying one foodstuff.

The Prerow value is a measure of how healthful the food is. With the Prerow value a decision whether a certain nutrition situation is better or worse than another can be made. Within a certain nutrition situation answers can be obtained to questions like what happens if less or more of one foodstuff is eaten while the rest remain constant.

The example in Figure 10 illustrates a typical situation. Starting with the actual intake obtained by a diet protocol of an average German man it can be calculated what happens, for example, if less or more sausage is eaten and all other foodstuffs are held constant. In this example, more sausage causes the Prerow value to deteriorate and less sauage improves this value (Figure 10a). The reverse situation is found with vegetables; more vegetables improve the Prerow value (Figure 10b).

If two foodstuffs, for example sausage and vegetables, are varied instead of a curve, a response surface is the result when the Prerow value is plotted. It is evident that the simultaneous reduction of the intake of sausage and the increased consumption of vegetables is the shortest way to optimize the Prerow value and thus comes closer to recommendations (Figure 11).

In reality, of course, this will be an n-dimensional discrete (because only changes in kitchen units are made)

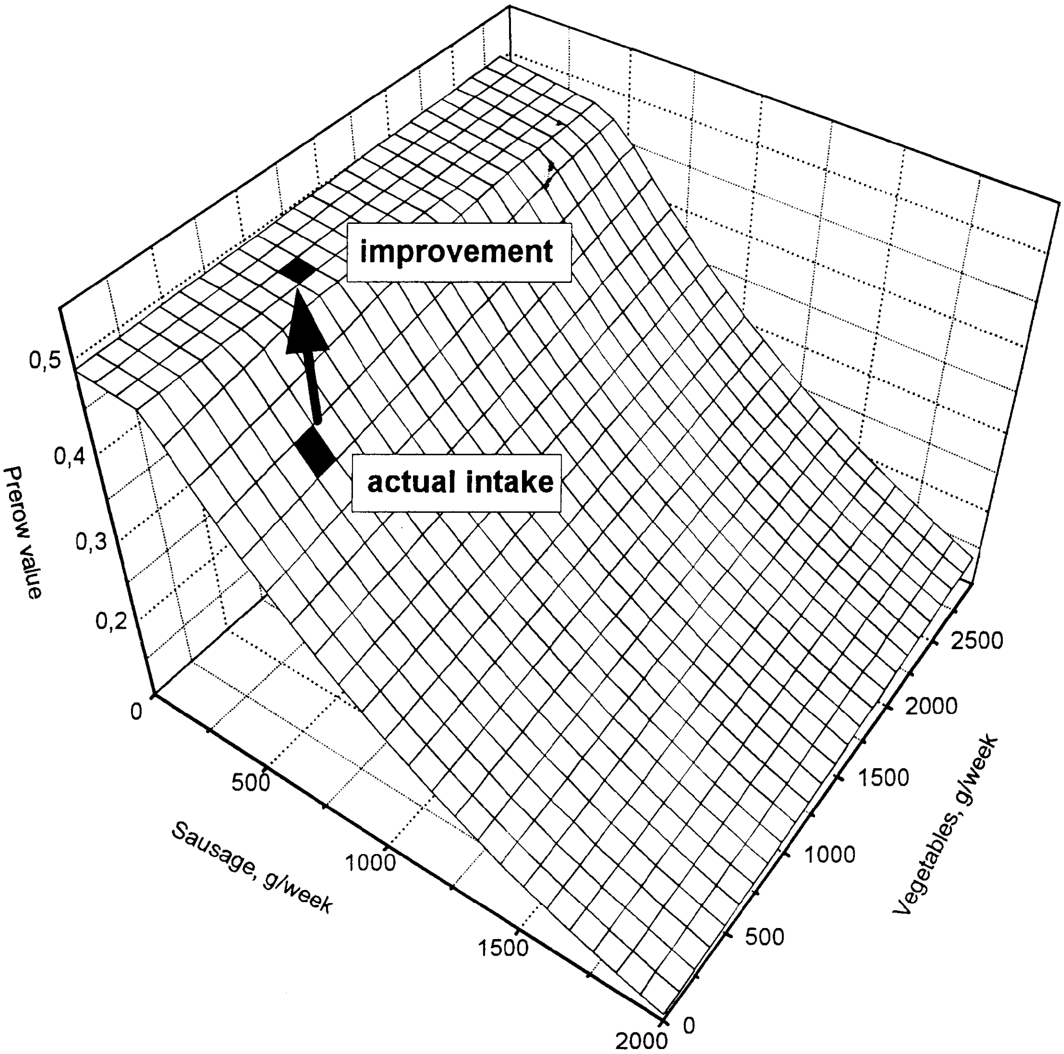

Figure 11 Variation of the Prerow value when varying two foodstuffs.

decision space. It cannot be plotted, but a computerized decision support system can be developed which calculates the gradient and thus finds points in the nutrition landscape near to the starting point but in good agreement with the recommendations. Experience with many nutrition consultations shows that the acceptance of such recommendations are good because this method tries to make only small changes in nutritional behaviour (Hahn *et al*, 1995).

Applications of methods to nutrition education

The fuzzy sets described above and the method of fuzzy decision making with optimization discussed were applied to a typical German man, aged 49 height 170 cm, moderately overweight (79 kg) with little physical activity. The nutrition behaviour is typically German, too. The main probems arise from the unfavourable relation between fat and carbohydrate intake and the high intake of alcohol. Some smaller problems are also found (too little dietary fibre, too much sodium). The Prerow value of 0.409 indicates that the health status of this man will deteriorate if his nutrition behaviour continues.

Table 1 shows a complete nutrition analysis and recommendations (variations of foodstuff in kitchen units, for example less beer, less sausage, more vegetables) for the above mentioned man. After optimization, the Prerow value of 0.883 indicates a desirable diet. The fuzzy values obtained for each nutrient are above 0.9, which corresponds to a verbal interpretation of a good supply of all nutrients. To reach this, 41 kitchen units changes within 7 d are to be made. This is an average change of only about 6 kitchen units per day. If one week is compared with another the standard deviation in nutritional behaviour of individuals is on average about 5–6 kitchen units. Therefore, the recommendation is not bigger than the standard deviation and has a direction instead of a statistical distribution.

The method described here is also applicable to optimization of nutrition with modified fuzzy sets for special diets.

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Table 1 Analysis and optimization of the consumed food

Name: John Miller	*Recommendation group: E25-51 M*	*Feb. 9, 1996*
	Analysis this is what you ate	*Optimization this is what you should eat*
The fuzzy value lies between 0 and 1. It evaluates a single nutrient. The Prerow value is the result of application of the operator 'harmonised minimum' to the fuzzy values of all nutrients and should be close to 1.	Prerow value: 0.409	Prerow value: 0.883

Nutrient contained:

Main nutrients

Nutrient	*Reference/d*	*Act. intake/d*	*Fuzzy value*	*Opt. intake/d*	*Fuzzy value*
Fat calories	500.0 kcal	797.3 kcal		512.4 kcal	
In % of energy	25.0%	38.9%	0.45	28.5%	0.95
Carbohydrate calories	1200 kcal	745.7 kcal		905.3 kcal	
In % of energy	60.0%	36.4%	0.49	50.3%	0.91
Energy, total	2000 kcal	2049 kcal	1.0	1798 kcal	0.98
Water	2.001	2.051	1.0	1.961	1.0
Essential fatty acids	12.0 g	11.9 g	1.0	9.01 g	0.97
Protein	59.0 g	83.4 g	0.99	74.5 g	1.0
Dietary fibre	40.0 g	17.6 g	0.78	28.2 g	0.91

Fat-soluble vitamins

Vitamin	*Reference/d*	*Act. intake/d*	*Fuzzy value*	*Opt. intake/d*	*Fuzzy value*
Vitamin A (retinol equiv.)	1.00 mg	1.98 mg	1.0	2.67 mg	1.0
Vitamin A (retinol)	< 1.50 mg	290 μg	1.0	303μg	1.0
Vitamin D	5.00 μg	3.00 μg	0.99	7.50 μg	0.98
Vitamin E	12.0 mg	10.5; mg	1.0	12.6 mg	1.0

Water-soluble vitamins

Vitamin	*Reference/d*	*Act. intake/d*	*Fuzzy value*	*Opt. intake/d*	*Fuzzy value*
Thiamin (vitamin B1)	1.09 mg	1.82 mg		1.32 mg	
Relative to energy intake	0.544 μg/kcal	0.890 μ/kcal	1.0	0.732 μg/kcal	1.0
Riboflavin (vitamin B2)	1.70 mg	1.42 mg	0.96	1.33 mg	0.92
Niacin equiv.	15.1 mg	34.7 mg		30.7 mg	
Relative to energy intake	7.54 μg/kcal	16.9 μg/kcal	1.0	17.0 μg/kcal	1.0
Pantothenic acid	6.00 mg	5.16 mg	1.0	5.43 mg	1.0
Pyridoxin (vitamin B6)	1.8 mg	1.95 mg		1.96 mg	
Relative to protein intake	30.5 μg/g	23.4μg/g	0.94	26.3 μg/g	0.98
Biotin	60.0 μg	43.3 μg	1.0	50.4 μg	1.0
Folic acid, total	300 μg	218 μg	0.99	255 μg	1.0
Cobalamin (vitamin B12)	3.00 μg	3.80 μg	1.0	3.5 μg	1.0
Vitamin C	130 mg	181 mg	1.0	214 mg	1.0

Macrominerals

Nutrient	*Reference/d*	*Act. intake/d*	*Fuzzy value*	*Opt. intake/d*	*Fuzzy value*
Sodium	2.00 g	4.29 g	0.75	3.40 g	0.91
Potassium	3.00 g	3.43 g	1.0	3.68 g	1.0
Calcium	900 mg	613 mg	0.94	654 mg	0.96
Magnesium	350 mg	379 mg	1.0	410 mg	1.0
Phosphorus	1.4 g	1.4 g	1.0	1.41 g	1.0

Microminerals

Nutrient	*Reference/d*	*Act. intake/d*	*Fuzzy value*	*Opt. intake/d*	*Fuzzy value*
Iron	10.0 mg	14.5 mg	1.0	16.8 mg	0.99
Zinc	9.00 mg	10.7 mg	1.0	10.9 mg	1.0
Copper	1.70 mg	2.33 mg	1.0	2.72 mg	1.0
Manganese	3.50 mg	5.24 mg	1.0	7.08 mg	1.0
Fluoride	2.00 mg	480 μg	0.87	612 μg	0.91
Iodine	200 μg	114 μg	0.94	123 μg	0.96

Other substances

Nutrient	*Reference/d*	*Act. intake/d*	*Fuzzy value*	*Opt. intake/d*	*Fuzzy value*
Cholesterol	0 mg	320 mg	0.88	272 mg	0.92
Sucrose	0 g	26.0 g	37.6 g		
Relative to energy intake	0 mg/kcal	12.7 mg/kcal	0.98	20.9 mg/kcal	0.94
Alcohol	0 mg	22.1 g	0.53	9.00 g	0.92

(*continued*)

Table 1 (*continued*)

Total consumption per week

Food	*Act. intake/g*	*Change/g*	*Opt. intake/g*	*Portion*
Bread	240		240	6 slices
Rolls	325		325	13 halves
Wholewheat Rolls	180	+60	240	8 halves
Wholemeal bread	250	+200	450	9 slices
Butter	120		120	15 portions
Sausage	490	−210	280	8 portions
Marmelade	42		42	6 teaspoons
Honey	7		7	1 teaspoon
Cheese, 20–40% fat	70		70	2 portions
Cheese, >40% fat	105		105	3 portions
Muesli	60		60	2 cups
Coffee	3750		3750	25 cups
Tea	0 g	+150	150	1 cup
Milk	600		600	3 glasses
Eggs	110		110	2 pieces
Fruit juice	1400		1400	7 glasses
Vegetables juice	2000		2000	10 glasses
Beer	2980	−1980	1000	3 bottles
Wine	300	−150	150	1 glass
Spirits	20		20	1 sm. glass
Liqueurs	20		20	1 sm. glass
Fruit cake	0 g	+100	100	1 piece
Cake	70		70	2 pieces
Potatoes, cooked	100		100	1 piece
Potatoes, mashed	300		300	3 cups
Rice	450	+150	600	4 cups
Noodles	200	+100	300	3 cups
Roast Pork	125		125	1 piece
Fried sausage with curry	300	−300	0 g	0 pieces
Thick Frankfurter	500	−500	0 g	0 pieces
Fish, fried	200		200	1 portion
Fish, preserved	0 g	+200	200	1 can
Bouillon	500		500	2 plates
Sauce, gravy	15		15	1 spoon
Sauce (ragu)	45		45	3 spoons
Vegetables, steamed	450	+1050	1500	10 cups
Salad with oil	300		300	2 cups
Apple	125		125	1 piece
Banana	150	+450	600	4 pieces
Orange	300		300	2 pieces
Duck, cooked	150		150	1 portion

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