Obesity by choice: the powerful influence of nutrient availability on nutrient intake

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Received 10 December 2001; accepted in final form 28 January 2002

Tordoff, Michael G. Obesity by choice: the powerful influence of nutrient availability on nutrient intake. Am J Physiol Regulatory Integrative Comp Physiol 282: R1536–R1539, 2002; 10.1152/ajpregu.00739.2001.—The consumption of nutrients by rodents is markedly influenced by the number of containers of each nutrient provided. Most rats given a choice from separate sources of protein, carbohydrate, and fat thrived if given one cup of each but half failed to thrive if given one cup of each and three extra cups of carbohydrate or fat. Rats given five bottles of sucrose solution and one bottle of water became fatter than rats given five bottles of water and one of sucrose. These studies in rats may point to a model for human obesity, in which the availability of food can override physiological controls of ingestion.

Pioneering studies in the 1930s showed that rodents can thrive when required to select a diet from separate ingredients (17, 18). This “nutritional wisdom” is generally considered to be the physiological basis of food selection, although it can be tempered by other factors such as taste hedonics, past experience, and social communication (3, 4, 19, 25, 26). Our current understanding of the mechanisms underlying food selection is based almost entirely on laboratory and farm studies in which animals were allowed to choose between separate containers of nutrients. In every case, the animals received one container of each nutrient. Here, we report that manipulation of the number of nutrient containers available can have profound effects on nutrient choice, even to the extent that they override the physiological controls of nutritional wisdom.

METHODS AND RESULTS

Experiment 1: influence of macronutrient choice on macronutrient selection. In this experiment, rats were given a choice between separate sources of solid carbohydrate (CHO), fat, and protein, but in addition to this standard choice of macronutrients, some rats received three “extra” cups of protein, CHO, or fat. Thirty male Sprague-Dawley rats [Charles River, Crl:CD(SD)IGS BR] were maintained under standard conditions (23°C, 12:12-h light-dark cycle) with powdered Purina Rodent chow (no. 5001) to eat and deionized water to drink until the rats were ~10 wk old, when the experiment began. Each rat was housed in a 20 × 18 × 25-cm stainless steel cage designed for conducting diet selection experiments (11). Food was available from stainless steel cups (7 × 7 × 3 cm) with spill-proof lids that were placed in each corner and at the center of the longest sides of the cage.

Sources of protein (casein), CHO (a mixture of cornstarch, dextrin, and sucrose), and fat (a mixture of Crisco vegetable shortening and safflower oil) each contained micronutrients and vitamins as described elsewhere (16). Body weights and intakes of each source were measured (to the nearest 0.1 g, corrected for spillage) every day. Fresh fat was provided every 2 days; water and the other nutrients were replaced as needed.

This experiment was terminated after 8 days because four of the seven rats given extra cups of CHO and three of the seven rats given extra cups of fat ate so little protein they failed to thrive. That is, their average daily intakes of protein were <15 kcal/day, and they lost body weight. In contrast, all eight of the rats given extra protein and seven of the eight rats given just one source of each macronutrient thrived well (difference in frequency, \( \chi^2 = 8.12, df = 3, P < 0.01 \)). Providing rats with extra cups of CHO or fat thus led to life-threatening protein malnutrition, even though protein was freely available in their cages.

The 22 rats that had acquired the habit of eating protein were reassigned to one of three groups, matched for protein intake and body weight. These were given the standard three cups of macronutrients (n = 8) or the three macronutrients plus three extra cups of CHO (n = 7) or fat (n = 7). Body weights and intakes of these animals were measured every 2 days and analyzed by two-way mixed-design ANOVAs, with factors of group and time. Under these conditions, the control group ate more protein, the group with extra CHO ate more CHO, and the group with extra fat ate more fat than did the other groups (P values < 0.05; Fig. 1). Over the 20-day test, these differences remained more-or-less constant. There were no differences in body weight gain or final body weight,
Rats given sucrose solution to drink in intake and obesity. Could override energetic constraints on intake. Extra CHO uence the body weight of female Sprague-Dawley rats in review, see Ref. 15). In this experiment, we attempted addition to their maintenance diet often become obese (for significantly higher than energy intakes of the other two signifi but total energy intake of the group with extra CHO was significantly higher than energy intakes of the other two groups [total energy intakes (kcal/day): control = 104 ± 1, extra CHO = 118 ± 5, extra fat = 107 ± 3; F(2,20) = 4.14, P = 0.03]. Thus access to multiple sources of a single nutrient biased intake toward that nutrient and, at least for CHO, could override energetic constraints on intake.

Experiment 2: influence of sucrose solution choice on energy intake and obesity. Rats given sucrose solution to drink in addition to their maintenance diet often become obese (for review, see Ref. 15). In this experiment, we attempted to influence the body weight of female Sprague-Dawley rats (weighing 238 ± 2 g at the start of the experiment) by manipulating their access to sucrose solution. The rats received to drink for 35 days 1) just one bottle of water, 2) five bottles of water and one bottle of 32% sucrose solution, or 3) one bottle of water and five bottles of 32% sucrose solution. Rats in the six-bottle groups (n = 12 each) were housed in stainless steel guinea pig cages (41 × 56 × 23 cm) with pine shavings on the floor. Powdered Purina rodent chow no. 5001 was available from a glass jar, and fluids were available from 50-ml inverted centrifuge tubes with rubber stoppers and stainless steel drinking spouts. When six tubes were available, the tubes were lined across the front of the cage at ~3-cm intervals and held in place by steel springs. The fourth tube from the left contained water, and the rest contained sucrose (or vice versa). Rats in the control group (n = 12) were housed in standard cages (18 × 24 × 18 cm) with the same food and a single tube of water. Food and fluid intakes were measured daily, and body weights were measured twice a week. Energy intake was calculated from the sum of sucrose intake (1.28 kcal/ml) and food intake (3.4 kcal/g). To provide more stable results and simplify data analysis, average intakes over each 4-day period were used in presentation and analyses.

At the end of the experiment (day 36), the rats were fasted overnight to remove gastrointestinal contents and then killed by anesthetic overdose. Their shaved carcasses were homogenized, and extracts were analyzed for fat content (13). Differences between groups were determined using two-way ANOVAs (group × day) for the intake measurements and one-way ANOVAs for body weight and fat content.

The rats with five sucrose bottles drank significantly more sucrose and consumed more energy than those with one sucrose bottle, both throughout the test [sucrose, F(1,22) = 40.7, P < 0.0001; energy, F(2,33) = 32.8, P < 0.0001] and for every 4-day period (P values < 0.01, except energy on days 29–32), with the differences being greatest at the beginning of the test period [group × time interactions, F(8,176) = 6.88, P < 0.0001 and F(18,297) = 4.42, P < 0.0001, respectively; see Fig. 2]. Significant differences between the groups in body weight gain emerged on day 8 [F(2,33) = 3.89, P = 0.031] and remained for the rest of the experiment.

The rats with five bottles of sucrose drank more than did the rats with only one bottle. Although their food intake decreased in partial compensation for the additional energy ingested as sugar, overall they consumed more energy than did the other groups. They gained significantly more weight than did controls after 8 days and significantly more weight than did rats with only one bottle of sucrose after 16 days. The group with only one bottle of sucrose and five of water consumed more energy throughout the test period and gained

![Graph](http://ajpregu.physiology.org/)
It is well known that obesity can be induced by providing rats fed a nutritionally complete diet with a sugar solution to drink, although this method is not always successful (reviewed in Ref. 15). Here, we found that obesity was greater and developed more rapidly when several sources of sucrose solution rather than just one source were available. Sucrose intakes were particularly high during the first few days of access but remained higher than those of the group with only one sucrose bottle throughout the 5-wk test period. It is noteworthy that the group with one sucrose bottle gained significantly more weight than did controls without sucrose to drink, but only after 33 days of sucrose access, which is a modest rate of weight gain compared with similar studies (see Ref. 15). It would be interesting to know whether providing these rats with five water bottles diluted exposure to sucrose and thus retarded the development of obesity relative to the more usual test procedure, where rats receive only one sucrose bottle and one water bottle.

We suspect that availability-based overconsumption is related to the “variety effect,” in which rats given foods of different flavors or textures overconsume relative to those given food of only one flavor or texture (e.g., Refs. 20, 21). Variety has been suggested as a cause of the obesity produced by feeding rats a diet of supermarket foods (8, 23). However, unlike the results seen with sucrose here, there is little evidence that variety has more than a transient effect on intake, and by itself it does not lead to obesity (12). Indeed, the present results argue that simply providing multiple sources of food stimulates intake and thus may contribute to, and in some circumstances even account for, the variety effect. At the least, the present results illustrate that interpretation of earlier nutrient choice and supermarket diet studies is difficult because they lack appropriate controls for the number of nutrient sources provided (see Ref. 10 for additional problems).

The mechanisms underlying availability-based overconsumption are unknown. Overconsumption due to food variety is usually attributed to hedonic effects or the lack of sensory-specific satiety (e.g., Refs. 20, 21), but these explanations are not informative from a physiological perspective. With respect to availability-based consumption, we think it more likely that with many sources of nutrients available, the rat simply takes advantage of the additional opportunities to ingest: the rat eats more because it encounters food more frequently. One implication of this is that the rat eats simply because the food is there and not in response to nutritional needs. This is an unorthodox explanation of consumption by the rat, but it is generally accepted to be the case for humans. Providing multiple sources of sucrose may also exacerbate obesity because, all things being equal, the rat has to expend less energy traveling to a source of calories than if only one bottle of sucrose is available.

The limits of availability-based overconsumption remain to be tested. In addition to the studies with solid nutrients and liquid sucrose reported here, we have found similar effects with mice given representative...
sweet, sour, salty, and bitter compounds, and the irri-
tant, alcohol (unpublished results). The phenomenon
therefore appears to encompass a wide spectrum of, if
not all, food items. It would be interesting to know
whether the relative positions or distance apart of
nutrient sources is critical, or whether rats select more
of a food presented in a big rather than small con-
tainer. There are also a number of potentially interest-
ning parametric investigations involving manipulations
of the number and difficulty of obtaining nutrients that
might tie the phenomenon into economic models of food
foraging (e.g., Ref. 2). A critical study will be to deter-
mine whether rats given more than five bottles of
sucrose develop even more pronounced obesity than
that seen here. Such experiments are more challenging
to conduct than single-nutrient source tests, but they
are probably more representative of the rats’ natural
foraging environment.

The finding that laboratory animals choose to eat
what is abundant has obvious relevance for husbandry
and for animals in the wild, including humans con-
fronted with many products in the supermarket. Re-
cent discoveries of new genes, hormones, and neuro-
transmitters involved in the control of ingestion and
body weight have led to a strong emphasis on the phys-
iological causes of obesity. Given the simultaneous
rise in the incidence of human obesity with the spec-
tacular increase in the availability of nutritionally
questionable foods, it appears that changes in avail-
ability rather than physiological mechanisms are more
likely to be responsible for the poor diet choice, hy-
perphagia, and obesity displayed by many humans.
The results observed here point to an animal model of
this “obesity by choice.”

I thank D. Pilchak, L. Curtis, S. Rabusa, J. Williams, A. Aqual-
iva, A. McDaniel, and A. Hargett for technical support. Drs. G.
Beauchamp, P. Breslin, M. Friedman, and D. Reed gave useful
comments.

This research was supported by National Institutes of Health
Grant AA-12715.

REFERENCES

1. Beck M and Galef BG. Social influences on the selection of a
protein-sufficient diet by Norway rats (Rattus norvegicus).


3. Galef BG Jr. Studies of social learning in Norway rats: a brief

4. Galef BG Jr. A contrarian view of the wisdom of the body as it

5. Harris LJ, Clay J, Hargreaves FJ, and Ward A. Appetite and
choice of diet. The ability of the vitamin B deficient rat to
discriminate between diets containing and lacking the vitamin.

6. Kon SK. LVIII. The self-selection of food constituents by the rat.

7. Lát J. Self-selection of dietary components. In: Handbook of
Physiology. Alimentary Canal. Control of Food and Water Intake.
Washington, DC: American Physiological Society, 1967, sect. 6,

8. Louis-Sylvestre J, Giachetti I, and Le Magnen J. Sensory
versus dietary factors in cafeteria-induced overweight. Physiol

9. McArthur RA and Blundell JE. Dietary self-selection and
intake of protein and energy is altered by the form of the diets.

10. Moore BJ. The cafeteria diet—an inappropriate tool for studies

11. Naim M, Brand JC, Christensen CM, Kare MR, and Van
Buren J. Preferences of rats for food intake and texture in
nutritionally controlled semi-purified diets. Physiol Behav 37:

12. Naim M, Brand JC, Kare MR, and Carpenter RG. Energy
intake, weight gain and fat deposition in rats fed flavored,
nutritionally controlled diets in a multichoice (“cafeteria”) de-

13. Ramirez I. Physiological and biochemical measurements in
relation to feeding. In: Feeding and Drinking, edited by Toates

14. Ramirez I and Friedman MI. Dietary hyperphagia in rats:
role of fat, carbohydrate, and energy content. Physiol Behav

15. Ramirez I, Tordoff MG, and Friedman MI. Dietary obesity
and hyperphagia: what causes them? Physiol Behav 45: 163–
168, 1989.

16. Reed DR, Friedman MI, and Tordoff MG. Experience with a
macronutrient source influences subsequent macronutrient

17. Richter CP. Total self-regulatory functions in animals and

18. Richter CP. Salt appetite of mammals: its dependence on in-
trinsic and metabolic. In: L’Instinct dans le Comportement des
Animaux et de l’Homme, edited by Cie Me. Paris: Libraires de

19. Riley AL and Clarke CM. Conditioned taste aversions: a
bibliography. In: Learning Mechanisms in Food Selection, edited
by Barker LM, Best MR, and Domjan M. Waco, TX: Baylor Univ.


21. Rolls BJ, van Duijvenvoorde PM, and Rowe EA. Variety in
the diet contributes to the development of obesity in the rat.

22. Sanders S, Ackroff K, Collier GH, and Squibb R. Purified
diets: some cautions about casein. Physiol Behav 33: 457–463,
1984.

Similarities to hypothalamic and human obesity syndromes.

24. Scott EM and Quint E. Self selection of diet. IV. Appetite for

25. Tordoff MG. Metabolic basis of learned food preferences. In:
Chemical Senses: Appetite and Nutrition, edited by Friedman
371–390.

26. Young PT and Falk JL. The relative acceptability of sodium
chloride solutions as a function of concentration and water need.