Effects of physical state (liquid-solid) of foods on food intake: procedural and substantive contributions1,2

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ABSTRACT Two types of procedures are described for the study of the effects of food attributes on food intake. One is concurrent evaluation in which the attribute is placed in the food, and the amount consumed is measured. The other is the preloading paradigm in which a food containing the attribute is given before a test meal and intake of the test meal is measured. From our work with both types of procedure in which we used foods in both solid and liquefied form, we conclude that the effects of food attributes on intake will differ depending on which procedure is used. Concurrent evaluation is recommended when the time course of the attribute is short-lived (few seconds to a minute). Preloading is the procedure of choice when the attribute’s effect is longer-lasting (several minutes to hours). When the same food was served in either solid or liquefied form, there was no difference in intakes of the two versions, but for liquefied form, the rate of consumption was faster, and meal duration was shorter, than for the solid. When a completely liquefied preload (soup) was given, intake in the following test meal was less for the same caloric load than when the preload was only partly in liquid form. Liquefied foods may be more efficient in producing satiety, as measured by food intake reduction, than solids. Because the two preloads were different across dimensions other than solid-liquid, more investigation of these other dimensions is needed. Am J Clin Nutr 1985;42:956–965.

KEY WORDS Appetite control, food intake, human feeding, meal preloads

Introduction

In order to examine the effect of the food attribute, physical state, on food intake and to identify approaches and methods for doing so, this paper will consider first the general scheme by which food attributes can contribute to the control of food intake. Next, suggested elementary conditions for the study of food intake in man will be presented, together with reasons for their employment. Two types of procedures will be described followed by examples of experiments which illustrate both their advantages and shortcomings. The experiments suggest that physical consistency of a single course of one food is unlikely to have much effect on amount of that course eaten, but that courses of solids and liquids could have strongly differing effects on subsequent consumption. However the crucial experiment to establish such an effect remains to be done.

Approaches to studying the effects of food attributes on food intake

There are three steps in the scheme of studying the effects of food attributes on intake. First, food stimulates bodily compartments, such as mouth, stomach, liver, and circulation. Second, these compartments in turn stimulate the brain. Finally the brain controls the peripheral nerves and muscles involved in the ingestive acts. Although it is possible empirically to study the effects of changes in food attributes on food intake, it is difficult to develop a systematic theory of how food intake ought to be affected by a particular attribute.

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such as its physical state (e.g., solid or liquid) without some idea where in the scheme the food attributes are acting and how these actions influence events further down the line. However, even without a coherent theory of the effects of solid or liquid versions of the same food on food intake, it is possible to develop some procedures for studying the effects, to collect data, and then to develop hypotheses for further testing. The work I shall report has in fact developed historically in that way. A new technique was developed for studying eating behavior in the laboratory. It was tested on food which could be served either as a solid or a liquid (1). Subsequently, a practical problem was offered to us for investigation (the effect of soup on food intake (2)), and its solution has led us to some new ideas about how foods should be tested for induction of satiety (3) and how the satiation process may operate.

The need for reproducible conditions

In order to examine attributes of foods that determine what, and how much, people eat, it is necessary to recognize that food selection and quantitative consumption are determined not only by attributes of the foods, but also by the physiological state of the subject and by the conditions under which the observations are made. Table 1 shows some of these conditions, which have been taken as a starting point for answering questions about attributes of foods that determine intake.

The advantages of employing the conditions listed in Table 1 are threefold. First, the number of uncontrolled variables is minimized. Second, it is possible to build in complexity by adding variables. Third, it is possible to duplicate results under conditions that are as nearly identical as possible. The use of homogeneous foods is suggested to increase precision in the measurement of consumption, which can vary in response to selection of particular nutrients, for whatever (sensory or postigestional) reasons. Normally eaten foods are recommended to facilitate attainment of stability, which could be delayed by presenting unfamiliar foods or familiar foods in an unfamiliar form. The major disadvantages of using the suggested basal conditions are that they are unnatural, require special conditions, and that only small numbers of subjects can be observed in a given amount of time. These disadvantages should not deter us from developing elementary and reproducible eating situations, for two reasons. First, the more reproducible the situation, the more consistent will be the results. Second, the more complex controls of natural eating should be predictable from combinations of simpler conditions. However, the emphasis on reproducible conditions should not blind us to the importance of repeatedly testing any attribute of food for cumulative effects on the same subject under the same, as well as under a variety, of conditions, before generalizing about the effects of the food’s attributes. The elementary conditions are meant to remind us of both the qualitative and quantitative controls of food intake.

Procedures for studying the effects of food attributes on food intake

There are two classes of procedures for studying the effect of food attributes on food intake, which we shall designate as concurrent evaluation and preloading paradigm. Each has advantages and pitfalls. In concurrent evaluation one measures intake of a food in which the attribute is placed. In the preloading paradigm a specified quantity of the food containing the attribute is served. Then, one measures intake of a course given subsequent to the preload. One difference between the two procedures is the temporal relationship between the independent and dependent variables. In the preloading paradigm variations
in food attributes are measured by their effects on subsequent eating, whereas in concurrent evaluation variations are measured by their effects on concurrent eating. Another difference between the procedures is the confounding of dependent variables. In concurrent evaluation the effect of an attribute is measured along with all other attributes in the same food, whereas in the preloading paradigm the effects of separate attributes are measured on a common dependent variable, the test meal.

The advantage of the concurrent evaluation method is mainly its simplicity. If one wanted to find out the effect on food intake of serving a food in solid, or liquid form, the simplest approach would be to prepare the identical food in both forms and serve it as a meal or series of meals. Likewise if one wanted to know whether a meal containing chicken noodle soup would result in a lower intake than one containing separate portions of chicken and noodles, the simplest approach would be to include each item in unlimited amounts in a meal and determine how much of each type of meal was consumed. This approach is fine if the objective is simply to determine the effect of a particular attribute on food intake or if one wants to test one type of food empirically against another. After describing an application of the concurrent method below we will point out its pitfalls.

Effects on intake of providing a food as either a solid or liquid

To illustrate the results of the concurrent evaluation to determine how serving a food in solid or liquid form affects intake, we served a yogurt and fruit diet either liquefied in a blender, or with the chopped fruit simply mixed into the yogurt (1). Subjects were tested after either 3 or 6 h following a standardized pretest meal. Intake was no different after either condition (see Fig 1). There were however, differences in the rate of consumption. These observations were extended to another group of subjects tested after either 1 or 21 h of deprivation and eating either the chopped fruit or the liquefied version of the yogurt and fruit diet (4). The liquefied version was eaten faster than the chopped (solid) version under both the 1 and 21 h conditions (See Fig 2). There was no interaction of type of diet (liquid-solid) with deprivation condition in either men or women (Fig 3).

**Pitfalls of concurrent evaluation**

There are at least three pitfalls of concurrent assessment. First, the multiple action of foods on possible independent mechanisms can lead to results which are difficult to interpret in relation to a mechanism of action. For example, a liquid food might be more satiating (and therefore tend to reduce intake more) than a solid, because it could stimulate nerve endings or promote release of hormones more readily than a solid. But it might not result in a lower intake because it could be more palatable or be eaten so quickly that any temporal cues associated with satiety induction would not have time to occur. Furthermore, liquids could empty from the stomach faster than solids and therefore activate postgastric satiety mechanisms sooner. On the other hand solids could remain in the stomach longer and activate satiety in that way. (See (1) for additional interpretations of these results of serving solid and liquid test meals of identical composition).

The second disadvantage is inadvertent biasing of the dependent variable by the independent variable. This problem is illustrated by an experiment we (Kissileff et al, 1984) did. We were interested in testing the hypothesis that a spontaneously ingested meal which included soup would be lower in terms of total
energy consumed than intake of a meal containing crackers, cheese, and apple juice. Because the soup-containing meal was more liquid than solid, we predicted that the meal containing soup would result in a lower intake because its greater volume would fill the stomach more effectively per calorie and, therefore, inhibit intake more than the combination. Subjects were given equal weights of the soup or of the combination as a first course (preload) on separate occasions and were then allowed to eat as much of the second course of macaroni and beef as they wanted. The two preloads, of course, differed in total energy content because of the differences in energy density. We were very excited about the outcome that total calorie intake was less for the meal which contained soup than for the meal which contained the combination, until we realized that, by combining the first and second courses into a single measure and converting to energy units, we had inadvertently included different amounts of the independent variable in our dependent variable (Fig 4), because of the conversion of the first courses into energy units. I call this the inadvertent bias problem because adding different amounts (the first courses converted to calories) to the true dependent variable (the second course) to make a composite dependent variable is analogous to loading the dice (adding a fixed weight to one side but not the other) before a throw and examining the outcome of such a throw. The outcome then has a random component plus the nonrandomly introduced difference between first courses. Of course, by not converting to energy units we would have avoided this problem. We would also have avoided the
problem by treating only the second course as a dependent variable. If we had simply allowed unlimited amounts of each course, as in a normal eating situation we would not have had a bias problem, either. However, in that case we would have had to contend with the third pitfall.

That is, the attribute becomes uncontrolled because the amount administered to the subject depends on the amount the subject consumes. If soup-containing, or highly-liquid, is considered an attribute of a meal, and one compares soup-containing with nonsoup-containing meals without controlling the amount of soup consumed, the soup-containing attribute is uncontrolled. Converting the weight of soup and meal to energy units, unfortunately, does not solve the basic problem of the lack of control. One solution to the problems posed by concurrent evaluation is to use the preloading paradigm with preloads given in fixed amounts.

**Advantages and disadvantages of the preloading paradigm**

By utilizing controlled amounts of different attributes as first courses we can develop a powerful analytical tool for studying the effects of food attributes as independent variables on food intake as a dependent variable. Because different foods with the same attribute can be used as independent variables, with a common test meal, serving as the dependent variable, it is possible to eliminate the confounding of several different variables latent in the concurrent evaluation approach, ie the first pitfall mentioned above. The second and third pitfalls are also eliminated because the preload is controlled and is not added to the test meal as a dependent variable. Besides eliminating problems inherent in the concurrent evaluation procedure, the major advantage of the preloading method is that it allows isolation and control of attributes or dimensions of the food, along which the effect on food intake is measured. In the concurrent paradigm all aspects of the food are measured at once. In the preloading paradigm only that aspect, along which the preload is controlled, influences intake. (See section on satiating efficiency below for further discussion of this advantage.)

Certain types of variables seem intuitively better suited to concurrent evaluation while others are better suited to the preloading paradigm. For example, it seems natural to study the effects of flavor, taste or temperature by incorporating that attribute into the meal and measuring intake. However, other attributes such as energy, density, or specific nutrients seem better suited to the preloading paradigm. A working hypothesis to explain this dichotomy in food attribute evaluation is that attributes which influence intake primarily by postingestive signals can be studied more effectively by preloading procedures while attributes which influence intake primarily by stimulating the oropharynx are more effectively studied by the concurrent method. The basis of this hypothesis is that postingestive signals tend to persist enabling them to act well after the preload has been consumed, whereas the more oropharyngeal signals terminate very quickly after food has been consumed, making them less effective in a preloading situation. Imagine for example the relative effects of zesty and bland preloads of identical composition, differing only mini-
mally in some physiologically inert component such as a spice, in comparison with identically tasting preloads of different starch content. Imagine again the same experiment conducted using the concurrent evaluation procedure. If the working hypothesis is correct, the zesty vs bland meal would have relatively little effect in a preloading situation, but would make a big difference in the concurrent situation, whereas the reverse would hold for the starch. That is the starch and nonstarch containing meals would be eaten in approximately equal quantity as meals but the starchy preload would be much more effective in reducing subsequent intake in a test meal. Therefore we must not only have hypotheses about the effects of food attributes, but also about how the effects of these attributes will be manifest in testing situations.

The preloading paradigm may allow more accurate determination of the effects of food properties on food intake, but it does not do so without problems of its own. The first of these problems is the temporal relation between the preload and test meal. Evidence from the work of Walike et al (5) and Booth (6) suggests that preloading effects may build to an optimal level and then dissipate. It is important to determine the shape of the temporal dependency of test meal intake on preload magnitude for each food quality being tested.

The other major problem with the preloading paradigm is the interpretation of possible sensory contrast effects. The work of Rolls et al (7) has explored this dimension of food effects, but it would be easier to partition the sensory and postingestive effects if the first course were controlled rather than allowing people to eat it until satisfied. If it turns out that preloading effects of any attribute are dependent to a great extent on the contrast between the sensory qualities of the preload and the test meal it would be necessary to develop a number of test meals which differed along the appropriate dimensions of the contrasts.

Satiating efficiency

Use of the preloading paradigm suggested above has led to development of a strategy for the testing of what could be called dimensions of food on satiation (3). This strategy is a logical extension of the general scheme of the effects on food intake stated earlier. It deals primarily with the inhibitory effects of food on food intake, but its converse, enhancement of intake by food attributes could be studied as well. If foods affect intake by their effects on different anatomical regions or by differential release of hormones, then it is reasonable to believe that food components may vary in the effectiveness with which they influence these physiological processes. In short, the theory (3) is that foods vary along a number of dimensions each of which makes a potentially measurable but presently unknown contribution to the satiation process. These dimensions are known to investigators, but they have not been studied systematically enough for any general statement to be made about their respective roles, either separately or in theoretically meaningful combinations. The dimensions include energy content, specific nutrients, ability of the food to distend the GI tract, rate of digestion and absorption, an array of sensory qualities, eg taste, flavor, color, texture, temperature, physical properties, eg viscosity, osmolality, consistency (chewable or not), particle size, and psychological dimensions such as perceived nutritional value, expectation of fullness, perceived energy density, and food class (meal, snack, type of meal). In fact the dimensions are not as numerous as the food items themselves but they are sufficiently diverse that any general theory of satiation must be prepared to measure and account for each significant contribution. It is not clear whether the solid-liquid attribute, which is the focus of this report, is actually a single dimension, or rather a combination of dimensions.

From the standpoint of the approach described earlier one step in understanding the mechanism of satiation is to quantify the relationship between reduction in intake and each of these factors, either separately or in combinations. This can be done most simply by giving preloads which are varied along one dimension at a time, holding the other dimensions constant, and using regression analysis to analyze the contribution of each factor alone.

Figure 5 shows some hypothetical examples of intake as a function of preload along the energy dimension. We call these intake-pre-
load functions. On the left are plotted two linear functions, and two nonlinear functions appear on the right. Since in the linear functions intake is reduced by a constant amount as the preload is increased, the slope of the line gives the amount of reduction in intake per unit increase in preload size. We shall refer to this relationship as the satiating efficiency, because it measures the effectiveness of the preload in suppressing test meal intake on a per unit basis. This measurement could be applied to different foods to determine empirically whether different components were more satiating per unit of energy, or it could be used to compare satiating effects along other dimensions such as weight, osmolarity, or viscosity. It is even possible to measure the relative contributions in variance units of several dimensions at once by treating each as a factor in an experimental design. Either analysis of variance or multiple regression could be used to determine the relative effects.

The slope is one parameter of the intake-preload function. The other is the intercept. The slope measures the effectiveness of all the variables in the preload which covary with the dimension along which the preload was varied, energy content or weight, for example. The intercept measures the hypothetical effect of all the variables in the preload which are invariant across levels of the preload. The elements of the preload which are invariant across levels of the preload are not actually known with certainty, since this notion has never been expressed before. However, either such elements must exist, or linear intake-preload functions do not exist, because, by definition, any linear function is the sum of two components, a constant, and another constant times the dependent variable. The constant could represent several possible variables separately or in combination. These could include the contrast between preload and the test meal, the cognitive effect of having two courses as opposed to a single-course meal, the stimulatory or inhibitory effect of palatability of the preload, independent of amount. In experimental animals the intercept could be altered by a surgical procedure or a genetic mutation which would have a constant effect on any procedure which involved variation of preloads. By comparing the intercept to the intake under no load conditions, it is possible to determine the effects of preloads, other treat-
ments, and their combination (a change in slope).

**Satiating efficiencies of solids and liquids**

In order to illustrate the value of the application of the concept of satiating efficiency to the study of the effects of attributes of foods, we (2) initially compared the satiating efficiencies of soup and a combination of crackers, cheese, and juice. The original purpose of this experiment was to provide evidence that soup is a highly satiating food. We, therefore, in accordance with our theoretical framework, compared intake of a test meal of macaroni and beef after two caloric levels of either soup or a combination of crackers, cheese, and apple juice. This experiment can also provide an indirect, although somewhat confounded, comparison of the effects on subsequent intake along the solid-liquid dimension, because all of the energy in the soup was in a liquid milieu, while only 31.6% of the energy in the combination was in a liquid. Ideally, one would want to perform this experiment using solid and liquid preloads of identical composition, although in practice this ideal may not be attainable, because addition of water is usually necessary to liquefy a product or addition of thickeners is necessary to solidify it. Water and thickeners then become confounded with the solid-liquid dimension. However, variation along the solid-liquid dimension could be inferred from preloads in which the proportions of liquid and solid were varied along some underlying dimension such as energy content or weight, as was done in the experiment described below.

Twelve subjects received two caloric levels of tomato soup and the same two caloric levels of crackers, cheese, and apple juice (38.5 and 115.5 kcal, each level), and another 12 subjects received chicken noodle soup and the same combination of crackers, cheese, and juice, each at the same two caloric levels as the group which got the tomato soup. The increases in preloads led to a significant decrease in intake of the test meal after both soups (Fig 6) but no significant decrease in test meal after the combination. These results suggest that foods in liquid form might be more satiating than those in solid form. It is interesting to note that the intercepts of the intake-preload functions were different for the two soups. In relation to the preexperimental baseline, the intercept for tomato soup was 123 kcal higher while for chicken noodle soup it was 50 kcal lower. We do not know what attributes of the two soups account for the differences in this effect. However, one interpretation is that something about tomato soup unrelated to the amount given as a preload increases food intake of a subsequent meal, while something about chicken noodle soup, unrelated to the

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**FIG 6. Intake-preload functions for tomato soup (upper panel) and chicken noodle soup (lower panel) in comparison with an equicaloric combination of crackers, cheese, and apple juice. Soups are shown by circles, the combination by squares. The triangles indicate mean intake under no preload condition, used at the screening test before subjects were accepted in the study. Each symbol is the group mean for 12 subjects. All four conditions (two preload levels of soup and two of the combination) were given to each subject, but separate groups of subjects were given each soup. (From Figure 1, [2]. Used by permission of Pergamon Press).**
amount given, reduces intake at a subsequent meal. It would be important to know whether these effects are related to the type of test meal or whether they would apply to any test meal.

The most obvious attribute of the soup that seemed responsible for the difference in satiating efficiency from the combination of crackers, cheese, and apple juice was the difference in bulk in relation to energy. The soups weighed more per unit of energy than the crackers, cheese, and juice. They also had less fat. We, (2, experiment 4) therefore, designed another experiment to determine the contribution to satiety of changes in preload weight and fat content at two different energy levels of preload. We used eight different combinations of energy level, fat content, and weight by changing the concentration (adding water or removing it by cooking) and fat content of tomato soup and gave each of eight women a test meal following each preload in a counterbalanced order. The preloads thus differed in water content and viscosity as well as in energy content.

The results were extraordinary. When we plotted intake of the test meal against weight of the preload there was no effect, much to our surprise. (See Fig 7). On the other hand, the effect of difference in energy level of preload was significant, and it was relatively uniform across the other factors (ie fat content and weight of preload see Fig 8). Intake after the high calorie preloads ranged from 68 g to 121 g less than after the low-calorie preload. The mean reduction was 94.2 ± 27.8 SED. Increasing the fat content resulted in a decrease in the satiating effect of soup, but it was not significant. Intake after high fat soups was 39.8 g larger than after the low-fat soups.

After the previous experiment, it was suggested that soup was more satiating than crackers, cheese, and juice because of its lower weight per unit of energy. The present experiment makes such an interpretation unlikely, and suggests that the mechanism by which soup results in greater suppression of intake is that soup may reach nutrient-sensitive receptors more quickly, or alternatively, it may activate them more strongly than crackers, cheese, and juice. There are also several differences in the physical properties and possible cognitive factors between soup and the combination preload that could account for their differences in satiating efficiency. These differences include temperature, osmolarity, consistency and particle size, ease of digesti-
ability, rate of consumption, use of utensils, and perception of the preload as filling or not. Experiments in which preloads of soup are varied along some of these dimensions would be the best way of evaluating the contributions to satiety of each of these factors.

In summary, it would be inappropriate to give an unqualified answer to the question, "what is the effect on spontaneous food intake of presenting food in solid or liquid form?" The answer to such a question depends in part on the procedure used. If the concurrent evaluation procedure is used, it appears that for at least one food which can be served in nutritionally identical forms as either a solid or liquid, the answer is that solids are eaten more slowly, and the cumulative intake curve exhibits less deceleration, than when the food is in liquefied form. However, intake is surprisingly no different. On the other hand, the soup studies suggest the possibility that, as preloads, equicaloric amounts of liquids are more effective in reducing subsequent intake than solids. However, this conclusion must be considered extremely tentative, given that the comparison on which it is based is confounded with several other variables than the solid-liquid dimension. The only other attempt (8) to address seriously the effect of the solid-liquid attribute on food intake was also confounded by differences between the preloads, other than solid-liquid. Ideally, one should use as preloads two different calorific or gravimetric amounts of a food served, either as a solid or a liquid, and follow them with a test meal. Indeed, to be safe, a number of different test meals should be used in this paradigm. It would then be possible to assess directly the satiating efficiency of this particular dimension. This experiment has yet to be performed. The last experiment described is another possible approach, ie presenting the preload diluted with different amounts of water added. However, this approach is not the same as using a preload which contains dense pieces which have to be chewed. Indeed, soup would seem to be an obvious vehicle for exploring this dimension of food attributes.

From a practical standpoint, the strategy proposed for evaluating foods for satiating efficiency along definable dimensions suggests an approach to developing technology that may be valuable in improving nutrition. By focusing on attributes of food which produce high satiety per unit of energy (high energy-specific satiating efficiency) one might be able to develop foods which are satisfying but not obesifying. The single test meal procedure should provide an economical initial evaluation of such foods.

I am grateful to David Booth, Stanley Heshka, and Joseph R. Vasselli for helpful suggestions on the manuscript and the ideas presented in it.

References