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Effects of food texture change on metabolic parameters: short- and long-term feeding patterns and body weight

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Labouré, Hélène, Sandrine Saux, and Stylianos Nicolaidis. Effects of food texture change on metabolic parameters: short- and long-term feeding patterns and body weight. *Am J Physiol Regulatory Integrative Comp Physiol* 280: R780–R789, 2001.—A complete diet was prepared with cooked pieces of meat, beans, cream starch, and water and presented to the rats in two different textures: a blended purée and a rough mixture that required a lot of chewing. We hypothesized that this texture modification might change both anticipatory reflexes and feeding behavior. Feeding rate, meal size, intermeal intervals, and their correlation were monitored in response to each texture. The long-term (6 wk) effect on body weight was assessed. Periprandial plasma glucose, insulin, glucagon, and lipid concentrations were assayed. Whole and background metabolism, respiratory quotient, and locomotion were measured using a computerized calorimeter of original design. In the short term, rats preferred the mixture. However, after 3 wk, they ingested more purée than mixture and gained more body weight per gram of food ingested as purée. Insulin response declined earlier with the mixture. During meals, glycerol and free fatty acid increased earlier with purée, whereas in the postprandial period, glycerol increased earlier with mixture. The metabolic rate, however, was not significantly affected. We concluded that texture, an everyday manipulation performed on food for human consumption, affects not only palatability of ingestants but also their metabolic management in the short and long term.

chewing; mixed food; anticipatory/cephalic responses; respiratory quotient; insulin; glucose; rats

ODOR AND/OR SIGHT OF FOOD as well as stimulation of gustatory and tactile afferents of the oral cavity initiate rapid, preabsorptive exocrine secretions (36), modifications of gastrointestinal motility (17), and changes in metabolic rate (MR) and respiratory quotient (RQ) (29). These are due to reflexes for the oral and gastrointestinal receptors (29). Among these early plasma and metabolic responses, plasma levels of glucose (29), insulin (58), glucagon (12, 47), catecholamine (56), and lipid metabolites (33, 57) frequently have been described.

These early modifications, referred to as cephalic or anticipatory reflexes (29), occur after activation of sensory endings of several nerves, including the vagus. These are the earliest physiological reactions after exposing an individual to food and they precede intestinal absorption. These reactions take place at the stage most liable to affect feeding behavior, pattern, and early metabolic consequences thereof. In addition, they may influence feeding behavior via early changes in metabolism itself (30). Hence, anticipatory reflexes may contribute to an early process of satiation, before substantial amounts of the ingested nutrients have reached the circulation.

Various organoleptic properties are reported to affect early plasma responses and feeding pattern. A variety of foods within a single meal increases insulin response (22, 26, 41, 45), as does the palatability of food (25). This insulin response modifies meal size and feeding patterns (25, 26). For example, the more palatable a meal, the greater the preabsorptive rise in insulin level, which, in turn, influences food intake (25, 35).

Texture is one of the components of the sensory properties of food, as much as gustatory, olfactory, and visual properties. It has been shown to affect the time of gastric emptying (5, 6, 11, 19) and of intestinal transit (39, 61). As a result, it can be hypothesized that texture might modify both anticipatory reflexes and feeding behavior. A number of experiments has been conducted to investigate the influence of texture on feeding pattern and body weight gain [Jordan et al. (21) in humans]. Shape and size of pellets consumed by rats influence the volume and the rate of feeding (9). Clifton et al. (8) have shown in rats that the reduction in the rate of food intake brings about a significant reduction of a meal size and enhances postprandial satiety, and rats fed pellets made softer by addition of water increase their consumption and body weight gain. Addition of sugars or starch, fat, or other nutrients that change not only palatability but also texture modifies feeding parameters (1, 37, 38, 40, 45). However, in all these studies, texture modification was accompanied by a difference in caloric content and density, which are liable to affect digestive and absorptive processes.

In the present investigation, great care was taken to avoid modifying caloric density and nutrient composi-

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tion, and the investigated parameters included assessment of feeding pattern as well as periprandial plasma metabolic factors and metabolism itself. Texture was modified by mixing a balanced diet made of various components that required, at least in humans, a consistent process of mastication before swallowing. Given the history of our laboratory (29), our attention was directed particularly to the early metabolic responses related to anticipatory reflexes. In addition, the long-term effects of ingesting the two different textures on feeding and body weight were investigated.

MATERIALS AND METHODS

Male Wistar rats (Iffa Credo, L'Arbresle, France), weighing 260–280 g at the start of the experiment, were used. Room temperature was maintained at 21 ± 1°C, and the lights were turned on from 0700 to 1900. Standard chow (Extralabo M25C; Pietrement, Provins, France) and tap water were available ad libitum unless otherwise stated. Body weight was measured daily.

The experimental food was prepared as a mixture of cooked kidney beans (Vivien Paille), cubes of cooked meat (beef), liquid cream (Bridel), starch (Roquette), and completed with water to reach 100 g. The nutrient composition of 100 g of food was 4.5 g protein, 16.6 g carbohydrate, 4.7 g fat, 0.23 g minerals, and 2 mg vitamins. The food was cooked and then two different textures were prepared; one was the original texture, referred to as the mixture, and the second was made liquid by blending the original food using a Vorwex macerator and is referred to as purée.

To avoid neophobia before the start of the experiment, all animals were presented with 3 g of each texture for a short period.

The specific methods and conditions implemented for each experiment will be described.

Experiment 1: Effect of Texture on Feeding Pattern

Rats were housed individually in cylindrical Plexiglas cages fitted to measure food intake by means of an electronic scale (Ohaus, CT600, accuracy ± 0.1, Florham Park) connected to an IBM personal computer via a multiport controller (Baytech 528; Baytech, Bay) with an RS-232 output. A computer-controlled acquisition program recorded and saved the data every 12 s. Changes in food cup weight were filtered and monitored using a program developed at the laboratory that yielded mean meal duration, meal frequency, mean intermeal interval (IMI) duration, mean rate of ingestion, and cumulative food intake.

Experimental protocol. All experiments were performed between 1800 and 1900, just before the light was turned off. For 2 days, all rats were deprived of food but not of water from 0800 to 1800 and then were allowed to eat standard powder chow from 1800 to 0800 the next day. Under *experiment 1a*, rats were separated into two groups. On *day 1* at 1800, one group was given the mixture, whereas the other group was fed the purée. They were both then fed powder chow during a 2-day interval before being given the other texture, respectively, on *day 4* at 1800. Therefore, one group was given first the mixture and second the purée, whereas the other group received the diets in the reverse order. Feeding pattern was monitored from 1800 to 0800 the next day when the animals were fed the experimental diet. In *experiment 1b,* both mixture and purée were presented simultaneously for 2 days with food cup location reversed each day. Feeding pattern for each texture was recorded during these 2 days.

Data analysis. A "meal" was defined as the period of consumption of a minimal quantity of 0.1 g (detection limit of the scales) over a minimum duration of 12 s (data-acquisition interval), preceded and followed by an interval of at least 4 min. To determine an appropriate minimum intermeal interval (IMI_{min}), log survivor analysis was used to analyze intervals between two bouts of intake of the two diets as recommended by Castonguay et al. (7, 46). With this method, IMI_{min} was found to be 4 min and is what distinguishes an intermeal pause from an IMI.

Statistics

Experiment 1a. To determine the possibility of an order effect, meal size (g), IMI (min), rate of ingestion (g/min), number of meals (*N*), and total food intake (g) were compared between first and second presentation using an ANOVA procedure. Cumulative food intake was tested by a repeated-measures ANOVA. In *experiment 1a*, the above-mentioned parameters did not differ and were therefore combined. To compare the effect of the two textures, meal size, IMI, rate of ingestion, meal frequencies, and total and cumulative food intake were analyzed by repeated-measures ANOVA and Student's paired *t*-test between time bins of cumulative food intake (pounds). Pearson's product moment correlation was used to determine relationships between IMI, meal sizes, and meal duration. Both the satiety ratio (IMI/meal size) and deprivation ratio (meal size/preceding IMI) were calculated and compared for the two textures.

Experiment 1b. To assess a possible difference between the two textures under *experiment 1b* and to compare *experiment 1b* with *experiment 1a*, we analyzed meal size, IMI, rate of ingestion, meal frequencies, and total food intake using repeated-measures ANOVA.

All results are expressed as means ± SE.

Experiment 2: Effect of Texture on Plasma Metabolic Parameters

To measure changes in plasma metabolic parameters before, during, and after food intake, blood samples were taken from nonanesthetized, freely moving rats without disturbing them.

At least 5 days before the experiments, all rats were equipped with an implanted jugular cardiac catheter. For this purpose, they were anesthetized with pentobarbital sodium (50 mg/kg; Sanofi) after pretreatment with a muscle relaxant, xylasine (Rompun; Bayer). The implanted venous catheter was set up according to a previously described technique developed by Steffens (50) and refined by Nicolaïdis et al. (32).

Before the experiment, to accustom the subjects to consume their food at once, rats were starved for 10 h in the light period (0800–1800) and trained to eat a chow powder 10 kcal test meal within 10 min. Each day the test hour was changed because previous studies have shown that insulin is released even in the absence of food when animals were conditioned by a set time presentation of food (55, 63).

On the first 3 days, rats ate the standard test-meal powder chow (3 g). After three consecutive presentations of this powder chow meal, on the fourth day, 8.3 g (10 kcal) of the two textures of the experimental diet were presented so as to prevent neophobia. The final session was performed on the fifth day. It consisted of presenting 10 kcal of one of the two textures at 1800 while blood was sampled before, during, and after the meal. After 2 recovery days, the same protocol was

repeated using the other texture, the order being random. After each experiment, the rats were fed chow powder again ad libitum. This 10-kcal ration was chosen because preliminary experiments had shown that this was the food portion for which there was prompt and complete ingestion regardless of the texture. During these tests, the rats were observed to lap the purée version without clear-cut mastication movements. In the case of the mixture version, the rats tore off pieces of beans and meats with their incisors and mastication was more perceptible.

In these experiments, it was important to prepare rats by meticulous handling and manipulation of the implanted catheter. During blood collection, rats were permanently connected to a syringe filled with heparinized saline (50 IU/ml) via polyethylene tubing. Blood samples (1 ml) were taken 5 min before presenting the purée or the mixture and then following it. Sampling that followed the onset of the meal was performed as follows: 1, 5, and 15 min after feeding initiation in one group; 3, 10, and 30 min in a second group; and 45, 90, 180 min in a third group. Blood samples of 1 ml were collected in chilled (0°C) centrifuge tubes containing 1 μl of anticoagulant heparin solution (25,000 U/5 ml) and immediately centrifuged at 4°C (2,000 rpm, 10 min). The plasma samples were divided into several small units for determination of glucose, triacylglycerol (TG), glycerol, and free fatty acids (FFA) (110 μl); insulin (50 μl) and glucagon (110 μl) were stored at −30°C. Blood glucose determinations were performed by a glucose-oxidase method, TG via enzymatic means (Hycel kit), and FFA and glycerol using a calorimetric enzymatic method (Oxoid kit and TG GPO-TRINDER kit, Sigma Diagnostic). Plasma immunoreactive insulin and glucagon were assessed by means of a radioimmunoassay kit (Sorin and Pharmacia and Upjohn).

Time patterns were analyzed by means of one-factor multivariate ANOVA with average concentrations before, during, and after feeding as dependent variables. Subsequently, *t*-tests for dependent means were used to compare individual concentrations of blood components with mean baseline values. The effect of presentation order for the mixture and purée was tested by a one-factor ANOVA over time. If P was greater 0.05, order influence was not significant. Hence, this parameter was eliminated and all the data for each texture were combined. Results were expressed as a percentage of basal level (value of the parameters 5 min before the beginning of the meal).

Experiment 3: Effect of Texture on Metabolism

This investigation was made possible by the development of an original device in our laboratory capable of monitoring not only the conventional MR and RQ but also the precise amount of locomotor activity and the background metabolism (BM). The latter is the rate of resting metabolism in an unrestrained animal, and it is deduced by extracting locomotion expenditure using a computerized system. The importance of assessing the BM is due, among other things, to the fact that it is purported to determine the occurrence of hunger and satiation (30).

The calorimetric apparatus used indirect calorimetry associated with a device for quantitative measurement of the power produced by the animal's locomotion as described in detail elsewhere (13–15). Briefly, this device was based on the principle of open-circuit flow-through calorimeter. Outdoor air was sucked through the chamber housing the rat (1.5 l/min) by a peristaltic pump. Cage air was then directed to an air dryer (filled with anhydrous $CaCl_2$), a flowmeter, and an O_2 and a CO_2 analyzer. The measurement of airflow and changes in O_2 and CO_2 content of the air that passed through the chamber allowed measurements of O_2 consumption and CO_2 release. We used these measures of O_2 consumption and CO_2 release to calculate the RQ, i.e., the ratio of CO_2 production over O_2 consumption and the total MR or total energy expenditure (Watt) using Lusk's equation (27). Spontaneous activity was quantified by integrating the electrical signal produced by three piezoelectric differential force transducers located under the cage. Background MR or thermic effect of food was computed as the cumulative increase in total energy expenditure induced by feeding and corrected for the energy expended specifically in relation to activity (14). The same calorimeter was also equipped with an electronic scale for weighing the food cup.

Animals were trained as in *experiment 2*. The night before metabolic recordings were made, rats were restricted to 10 g of standard chow. The next day they were placed in the calorimeter at 1400 with water ad libitum but no food available. At 1800, once the metabolic parameters had reached a stable baseline level, a calibrated meal of 10 kcal of one of the two experimental foods, chosen at random, was presented to the animals. Metabolic measurements were performed over the next 12 h.

Data analysis. RQ and total BM were compared using a two-way ANOVA design: mixture group $n = 11$ vs. purée group $n = 12$, time completed by a Student's *t*-test time-by-time (Statview, SAS Institute).

Experiment 4: Long-Term Effects of Texture Change on Food Intake and Body Weight

In *experiment 4a*, two groups of rats were used. Body weight ranged from 260 to 280 g at the start of the experiment. Each of these two groups received one of the two versions (purée or mixture) ad libitum for 6 wk. Their feeding patterns were monitored at night from 1900 to 0400. Twenty-four-hour food intake was measured daily, taking into account possible spillage. Body weight was measured every 2 days.

In *experiment 4b,* another group of six rats followed the same protocol as in *experiment 4a,* except that both the mixture and the purée versions were supplied permanently in two recording food cups, the position of which was randomly altered.

Data analysis was the same as the *experiment 1*.

RESULTS

Experiment 1

In *experiment 1a,* the order of presentation of the two textures did not affect the parameters under investigation, and therefore data were combined. Rats consumed the mixture more rapidly than the purée ($P < 0.01$). The number of meals was increased when rats consumed the mixture (Table 1). Cumulative food intake was increased in the mixture version and this was significant as early as the first 30 min (Fig. 1*A*). Meal size too was larger when rats consumed mixture. The satiety ratio was not significantly different for the two food textures, but the deprivation ratio was significantly higher for mixture than purée (0.5 ± 0.04 and 0.22 ± 0.02, respectively, $P < 0.0001$). Both premeal and postmeal IMIs significantly correlated with the size of meal in both mixture and purée versions (Table 2).

Table 1. *Microstructure of meal as a function of texture and presentation paradigm*

	Sequential Presentation		Choice Situation	
	Mixture	Purée	Mixture	Purée
No. of rats	20	20	22	22
No. of meal	12.84 ± 0.26†	9.25 ± 0.17	9.16 ± 0.55§	3.82 ± 0.41
Meal size, g	6.95 ± 0.46*	5.56 ± 0.42	5.49 ± 0.34*	3.39 ± 0.45
Meal duration, min	10.684 ± 1.043	10.276 ± 0.93	7.49 ± 0.36	7.23 ± 0.49
Mean feeding rate, g/min	1.16 ± 0.18†	0.598 ± 0.037	0.82 ± 0.052*	0.49 ± 0.046
IMI duration, min	35.8 ± 2.47	40.24 ± 2.57	31.95 ± 2.23†	78.78 ± 9.11
Total food intake, g	77.62 ± 3.04§	55.48 ± 2.27	53.12 ± 3.18§	16.33 ± 2.98

Values are means ± SE. IMI, intermeal interval. Significant difference between the 2 textures of meal for each kind of presentation: *$P < 0.05$, †$P < 0.01$, §$P < 0.0001$.

In *experiment 1b*, when both textures were available, meal frequency of mixture was three times higher than meal frequency of purée (Table 1 and Fig. 1*B*). When rats initiated feeding on the mixture, the meal size was 1.5 times larger than the meal size for purée and mixture was consumed twice as fast as purée. Thus total consumption was three times higher with mixture than with purée.

Experiment 2

The 10-kcal meal was entirely consumed within 15 min of presentation whether rats were given mixture or purée.

Basal values of the plasma variables were consistent with prior studies (glucose: 8.3 ± 0.09 mmol/l, insulin: 34 ± 1.35 μU/ml, glucagon: 167 ± 4 pg/ml, FFA: 0.51 ± 0.03 mmol/l, TG: 0.43 ± 0.04 mmol/l, and glycerol: 0.19 ± 0.08 g/l).

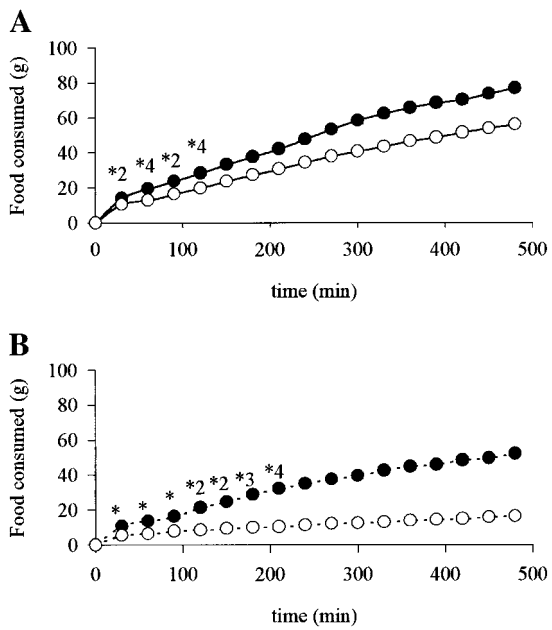

Fig. 1. Cumulated food intake when animals ate mixture (●) or purée (○) version of the same food in sequence (solid line, $n = 22$) or two-choice situation (dashed line, $n = 20$). *A*: mixture or purée available. *B*: mixture and purée available. Significant difference of food intake between textures (*$P < 0.05$, *2$P < 0.01$, *3$P < 0.001$, *4$P < 0.0001$).

As described previously (29), the first plasma glucose response was a drop in concentration 1 min after the onset of feeding ($P < 0.001$ for mixture and $P < 0.0001$ for purée; Fig. 2). As early as 3 min after the onset of feeding, plasma glucose increased ($P < 0.01$ for mixture and $P < 0.0001$ for purée). Plasma glucose was still rising at 15 min but decreasing at 30 min postfeeding initiation. Another increase was found in the 180-min sample. None of these changes was significantly different in the two groups of animals. No difference was found between areas under the curve.

Plasma insulin increased as soon as 1 min after the onset of feeding, and this increase reached its maximum at 10 min in the purée version and at 15 min in the mixture one (Fig. 2). By 180 min after the onset of the meal, plasma insulin reached its basal level. The only difference between the mixture and purée versions was found in the 15-min sample where the insulin level was higher for the mixture ($P < 0.05$) and in the 30-min sample where insulin remained high for the purée texture ($P < 0.01$). No difference was found between areas under the curve.

The increase in plasma glucagon became significant in the 10-min sample. This persisted at 180 min and reached a maximum 45 min after the onset of the meal (Fig. 2). No difference was found between areas under the curve.

A brief and also small significant change in TG was found in the 3-min sample from rats consuming the mixture version ($P < 0.001$) and in the 10-min and 15-min samples from rats consuming the purée ($P < 0.0001$, Fig. 2). A more persistent increase in TG started 45 min after the onset of the meal and persisted at 180 min. The rise in the TG in the purée group lasted longer than in the mixture group. No difference was found between areas under the curve.

The rise in plasma FFA was prompt and biphasic in both mixture and purée groups (Fig. 2). The first significant increase was found 1 min after the onset of feeding ($P < 0.0001$ for mixture and $P < 0.001$ for purée), and the second persistent increase was found 45 min and 180 min after the onset. No difference was found between areas under the curve.

Although less pronounced, the increase in glycerol was also prompt and biphasic (Fig. 2). This increase lasted 45–180 min and was more persistent in the

Table 2. *Correlations between meal size or meal duration and pre- and postmeal IMI duration for both textures*

Correlation		Mixture		Purée	
Meal	Interval	*r*	*P*	*r*	*P*
Meal size	Postmeal duration	0.20	<0.0001	0.43	<0.0001
Meal size	Premeal duration	0.14	<0.01	0.14	<0.02

mixture group. Area under the curve was higher in the purée than in the mixture version [$F(1,20) = 7.57$; $P < 0.01$].

Experiment 3

Figure 3 shows the effect of the two versions on the BM. As expected, BM showed a rapid increase. The initial rise was similar in both versions. Thirty minutes after the initiation of the meal, the increase was highly significant for both mixture ($P < 0.001$) and purée ($P < 0.01$). However, between 30 and 100 min after the onset of the meal, the BM that followed the mixture slightly decreased, but this decrease did not reach statistical difference ($P < 0.07$ at 60 min). The BM of both mixture and purée groups slowly returned toward basal levels in 475 min for purée and 415 min for mixture. Whatever the early small differences in the BM, the areas under the curve did not achieve statistically significant differences [$F(1,16) = 0.36$; $P = 0.55$] but tended to be greater with purée than with mixture (61.5 ± 11.1 and 53.86 ± 5.68 Watts, respectively).

Here too the RQ dramatically increased as previously reported (29). There was no difference on the effect on the RQ between the two textures (Fig. 3).

Experiment 4

Ingestion of the two textures exhibited a reverse pattern of preference (Fig. 4). The purée group consumed a mean of 106.4 ± 3.6 g/day during the 1st wk and then decreased its daily consumption to 101.21 ± 1.5 g/day in the 3rd wk and still further to 98.9 ± 1.9 g/day in the 5th wk. Rats in the mixture group began consuming the same daily amount as rats in the purée

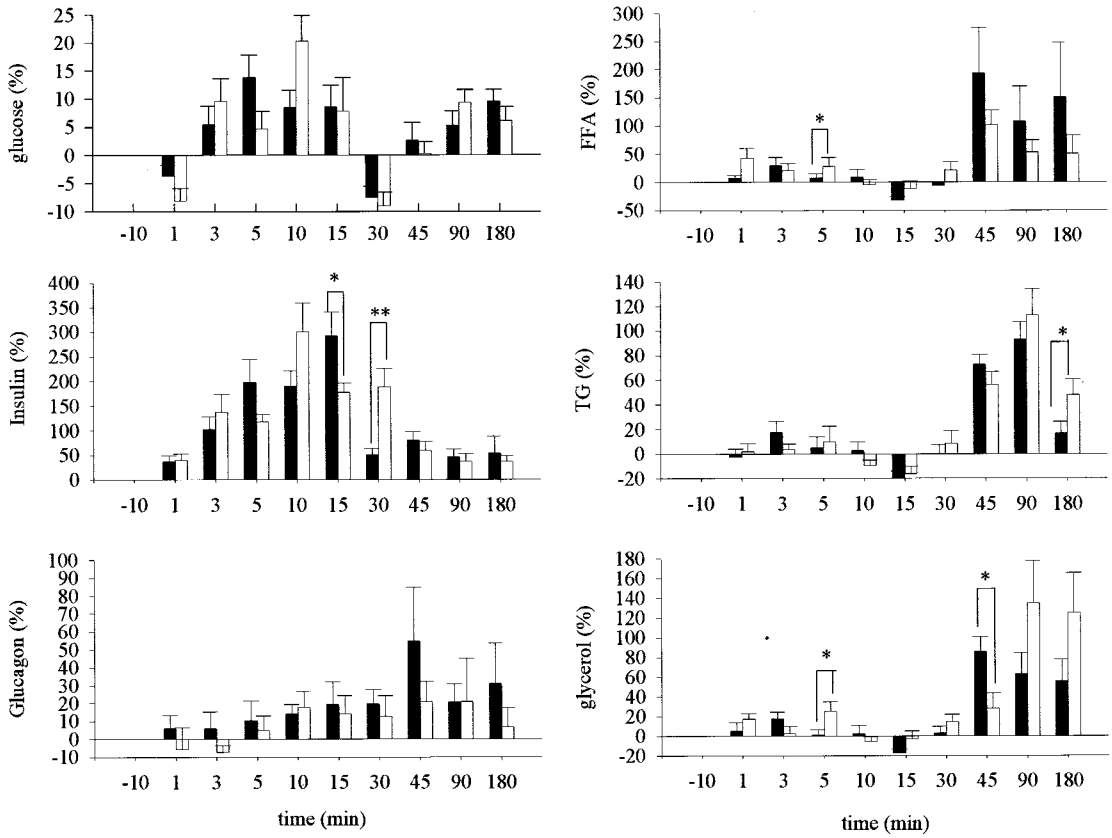

Fig. 2. Changes in plasma glucose, insulin, glucagon, free fatty acids (FFA), triacylglycerol (TG), and glycerol plasma concentrations in response to ingestion of the mixture (solid bars) or the purée (open bars) version of the same food. For mixture and purée, respectively, $n = 12$ and 6 for glucose, 14 and 18 for insulin, 10 with both textures for glucagon, 12 and 6 for TG, 12 and 6 for FFA, and 12 for both textures for glycerol. Significant difference of food intake between textures (*$P < 0.05$, **$P < 0.01$).

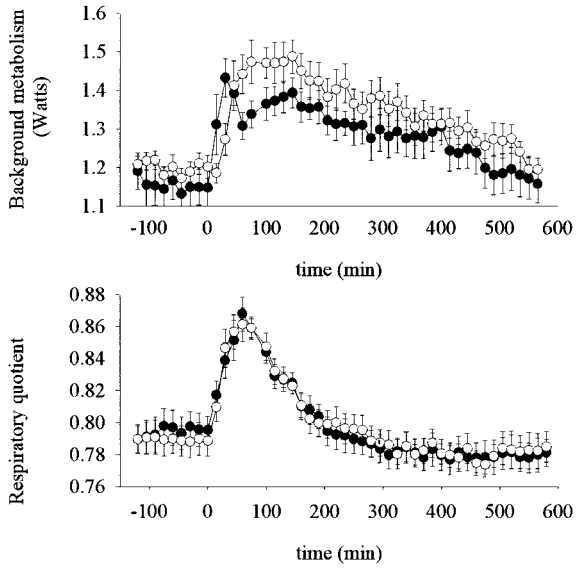

Fig. 3. Changes in backround metabolism and respiratory quotient (RQ) in response to ingestion of the mixture (●, $n = 11$) or the purée (○, $n = 12$) version of the same food.

group. However, they subsequently decreased their daily food mixture intake until the 5th wk (90.7 ± 1.8 g/day). These unexpected changes were more pronounced for the mixture ($P < 0.0001$) than for the purée ($P < 0.11$). The differences in mean daily consumption were significant in the 3rd, 4th, 5th, and 6th wk ($P < 0.05$, 0.0001, 0.01, and 0.0001, respectively). Changes in consumption arose from changes in feeding during the light period only. Analysis of feeding parameters also showed that the number of meals was higher in the mixture group [$F(1,34) = 16.86$; $P < 0.01$], and this was particularly apparent on the 2nd and 23rd days of the experiment (Fig. 5). Furthermore, each meal was larger in the purée group [$F(1,34) = 6.48$; $P < 0.05$; Fig. 5]. As in *experiment 1,* feeding rate was higher in the mixture group [$F(1,34) = 17.39$; $P < 0.01$] than in the purée group (Fig. 5). The duration of meal was shorter in the case of mixture [$F(1.34) = 8.12$; $P < 0.05$], particularly on the 1st day (Fig. 5). This duration decreased dramatically between the 1st and the 2nd wk of the experiment. Finally, the IMIs were longer in the purée group, and this difference was more pronounced from the 4th to the 6th wk of the experiment (Fig. 5).

Body weight increased normally during the 6 wk of the experiment, but this increase became more pronounced in the purée than in the mixture group [$F(1,5) = 10.0$; $P < 0.03$; Fig. 4]. The difference in body weight became significant in the 3rd wk. Differences in body weight gain could be accounted for by differences in food intake, the latter also being statistically larger from the 3rd wk. However, the ratio of body weight increase per consumed calorie was larger in the purée than in the mixture group ($P < 0.01$).

In *experiment 4b,* rats consumed both textures but the respective proportions of each varied following a particular pattern (Fig. 4). In the 1st wk, rats preferred the mixture version ($P < 0.001$), in the 2nd and the 3rd wk they ingested equal amounts of each version, and in the 3rd to 6th wk the preference was reversed ($P < 0.0001$).

Comparison of *experiments 4b* and *4a* showed that rats consumed more when they had access to both textures. Body weight increased normally, and this increase was the same as for rats in either texture group under *experiment 4a*.

DISCUSSION

In this investigation, particular care was taken to confine the difference between the two diets to texture only. It was also important to assess behavioral as well as autonomic responses to these two diets both in short- and long-term studies. Under these conditions, it is remarkable that some but not all responses do depend on texture. This is the first time that the effect of texture on short- and long-term feeding and behavior has been explored. It is also the first time that such an exploration has been associated with an assessment of metabolic parameters that may reveal the mechanism whereby the nature of ingestants affects their nutritional value.

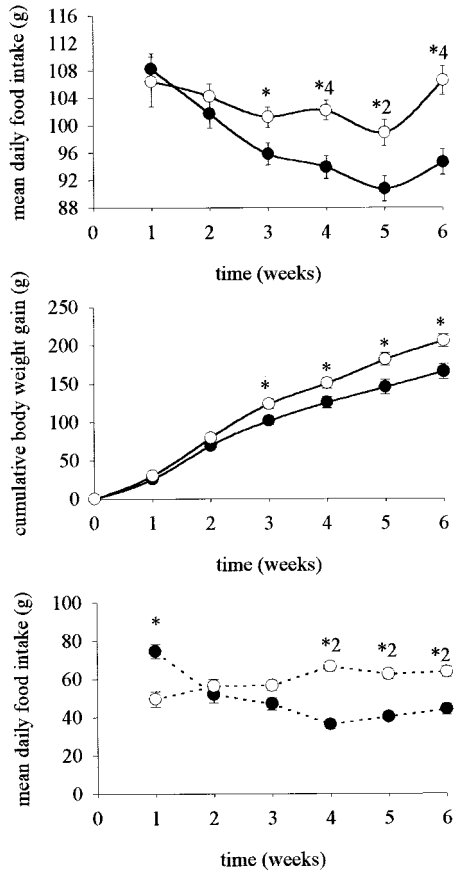

Fig. 4. Cumulative body weight gain in the sequential presentation and mean daily food intake in sequential (solid line) or choice (dashed line) presentation in response to ingestion during 6 wk of the mixture (●, $n = 6$) or the purée (○, $n = 6$) version of the same food. Significant difference of food intake between textures (*$P < 0.05$, *2$P < 0.01$, *4$P < 0.0001$).

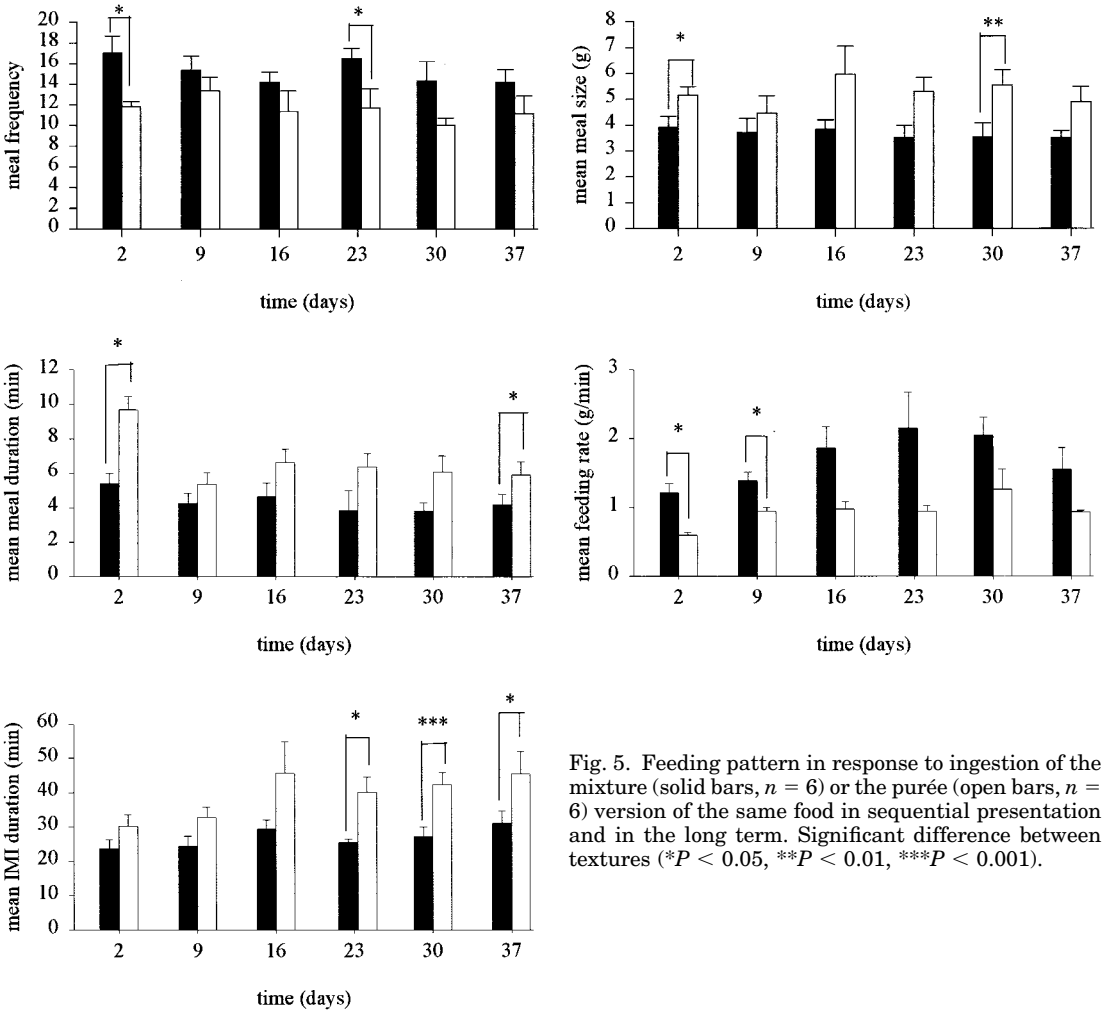

Fig. 5. Feeding pattern in response to ingestion of the mixture (solid bars, $n = 6$) or the purée (open bars, $n = 6$) version of the same food in sequential presentation and in the long term. Significant difference between textures (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$).

In the short-term experiments, and considering the consumatory responses, rats ingested the mixture more and more rapidly; meals were larger and their frequency was higher. Although larger, the mixture meals were not followed by an increase in the postprandial IMI as might be expected, i.e., the satiating effect of the mixture was reduced. This was confirmed by the deprivation ratio, also higher for mixture than for purée. These differences can be accounted for if it is accepted that the mixture is more palatable to the rat as borne out by *experiment 1b* whereby rats show a clear preference for the mixture. It is possible that the additional artifact that consists in blending the original ingredients was responsible for the reduction in palatability of the purée. In other experiments where rats were compelled to choose between powder and pellets, they showed a significant preference for pellets (2, 10, 28). It can be conjectured that the preference for the mixture is due to the variety of sensations produced by alternation of pieces of meat and vegetables compared with the uniform taste of the purée. Indeed, it has been shown that sequential changes in food flavors during the course of a meal induce an increase in consumption (23, 60). This is the sensory-specific satiety described by Le Magnen (23) and later by Rolls et al. (42–44). Furthermore, variety in the sensory properties of food has been demonstrated to be a major contributor to food palatability (20). In agreement with findings in the literature (8), it may be that the increased rate of ingestion of the mixture brings about a reduction in the size of meals.

The texture-bound differences in feeding parameters could be due to changes in circulating metabolic factors known to accompany and to affect feeding. *Experiment 2* was aimed at elucidating this question.

Before considering the differences related to texture, it should be noted that the early responses observed in this experiment agree with a number of previous studies on early metabolic changes (29).

As described in the literature, the insulin concentration rises within just a few minutes of initiation of food intake (4, 12, 51) and is still high at the end of the meal (3, 51). Glucose changes are also rapid. As we had shown in our first studies (29), glucose decreases below the basal level almost immediately. This early hypoglycemia that has been confirmed by other authors (12, 24, 52, 59) is probably due to the initial insulin release (18). We also found an early rise of FFA plasma con-

centrations (54). We here report a rise in glycerol parallel to the FFA profile. These early responses seem to be due to an early lipolysis that triggers rapid hydrolysis of stored TG (48). It is difficult to know whether the glycerol comes from the white adipose tissue or from our feed that contains more lipids than the food given in a study by Steffens et al. (54). The fact that contrary to previous reports glycerol increases concomitantly with FFA would seem to indicate that a lipolytic process concerning the white adipose tissue is involved (54). In agreement with the literature (49), the FFA profile is a mirror image of the glucose profile.

Under *experiment 2*, it was necessary to produce identical sensory stimuli except for texture. As a result, we had to alter the feeding protocol that had been applied to *experiment 1a*; instead of being presented ad libitum (as in *experiment 1*), meals had to be divided into equal portions and eaten entirely. Preliminary experiments on rats being fed while blood samples were taken via the implanted catheter had shown that a 10-kcal ration of mixture or purée was promptly and completely ingested. The drawback with this restricted ration is that it reduces the stimuli that elicit pre- and postabsorptive autonomic responses (the same observation holds for *experiment 3* on overall metabolism). Despite this disadvantage, some differences in plasma metabolic responses appeared. The insulin response increased at an earlier stage with purée and declined earlier in the mixture group. This earlier decline could account for the larger consumption of the mixture observed in *experiment 1*, because periprandial insulin is considered to be a potent factor inducing satiety (16, 31, 62). Some indexes of lipolysis were also different for the two textures. The 45-min elevation of glycerol was followed by a descending profile in the mixture group, whereas in the purée group, the glycerol profile was ascending. A small but significant increase in glycerol and FFA in the purée group also appeared in the 5-min sample that certainly corresponds to a preabsorptive response. As for the plasma TGs, they remained high in the 180-min sample from the purée group. These moderate differences perhaps indicate a slight enhancement in lipid metabolism when rats ingest the purée.

Figure 3 shows that the response of BM of mixture is identical to that of purée, but after 20 min it decreases and remains lower for >1 h. However, the range of these metabolism responses is such that the difference was not statistically significant. As stated previously, it may be that the small calibrated meal used in this experiment provided insufficient stimuli and therefore minimized the changes in metabolism compared with the changes that accompany the large meals observed in the free-feeding conditions under *experiment 1*.

In the first three short-term experiments, it was difficult to determine whether the mixture version was preferred only because of its sensory properties. An alternative explanation may be that the autonomic responses are different for the two textures and as such may affect feeding behavior, particularly in the long term. In that case, repeated exposures to the two textures may lead to the reversal of the rats' initial preference. Furthermore, if autonomic responses are different enough to affect the preference, they may also affect metabolism and therefore body weight gain. The last experiment was designed to shed light on these questions. The fact that in this experiment initial palatability-related preference for the mixture was gradually reversed in favor of the purée suggests that a Garcia-type phenomenon is taking place, i.e., that some beneficial postabsorptive action is associated with the ingestion of the initially less preferred purée. In fact, rats gradually ingested more purée than mixture. The possibility of a beneficial postabsorptive action deriving from the purée is also supported by the fact that concomitantly with the reversal in their preference, rats ingesting the purée exhibited greater body weight gain than those consuming the mixture. Texture might produce an initial effect on palatability and a subsequent effect on the metabolic management of carbohydrate-lipid metabolism that in the long term feeds back to the preference itself. Blending the ingredients may make them more readily digestible and therefore beneficial. Texture modifications need to be more thoroughly investigated because they are being increasingly used in the food industry and the kitchen. As under this study, they must examine both the short- and long-term effects and be associated with an assessment of as many physiological parameters as possible. Thus we will gain a better understanding of the way texture change affects our feeding behavior, its nutritional consequences, and its role as the neglected component of "taste" in physiology.

Perspectives

These rat studies are just the first step of our more extensive investigation in human nutrition made particularly necessary because industrialized societies increasingly use texture modifications of foods (soups, purées, expanded food). What do they do to us? How do they affect our physiological responses and, in the long term, body weight? These questions are even more crucial for humans as they chew and hold some of the nonblended foods in their mouths much longer than a blended preparation (e.g., 4 times longer in the case of the textures used in our rat experiment). In our experiment, we have chosen the typical comparison between a boiled mixture and its blended version. Other comparisons and other physiological parameters will shed more light on the consequences of this everyday practice of texture modification and on the physiological role of texture, a component of taste that has been so far only tentatively explored.

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