AJCN. First published ahead of print June 8, 2016 as doi: 10.3945/ajcn.115.129064.

Empty calories and phantom fullness: a randomized trial studying the relative effects of energy density and viscosity on gastric emptying determined by MRI and satiety[1,2]

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ABSTRACT

Background: Stomach fullness is a determinant of satiety. Although both the viscosity and energy content have been shown to delay gastric emptying, their relative importance is not well understood.

Objective: We compared the relative effects of and interactions between the viscosity and energy density on gastric emptying and perceived satiety.

Design: A total of 15 healthy men [mean ± SD age: 22.6 ± 2.4 y; body mass index (in kg/m^2): 22.6 ± 1.8] participated in an experiment with a randomized 2 × 2 crossover design. Participants received dairy-based shakes (500 mL; 50% carbohydrate, 20% protein, and 30% fat) that differed in viscosity (thin and thick) and energy density [100 kcal (corresponding to 0.2 kcal/mL) compared with 500 kcal (corresponding to 1 kcal/mL)]. After ingestion, participants entered an MRI scanner where abdominal scans and oral appetite ratings on a 100-point scale were obtained every 10 min until 90 min after ingestion. From the scans, gastric content volumes were determined.

Results: Overall, the gastric emptying half-time (GE t_{50}) was 54.7 ± 3.8 min. The thin 100-kcal shake had the lowest GE t_{50} of 26.5 ± 3.0 min, followed by the thick 100-kcal shake with a GE t_{50} of 41 ± 3.9 min and the thin 500-kcal shake with a GE t_{50} of 69.5 ± 5.9 min, and the thick 500-kcal shake had the highest GE t_{50} of 81.9 ± 8.3 min. With respect to appetite, the thick 100-kcal shake led to higher fullness (58 points at 40 min) than the thin 500-kcal shake (48 points at 40 min).

Conclusions: Our results show that increasing the viscosity is less effective than increasing the energy density in slowing gastric emptying. However, the viscosity is more important to increase the perceived fullness. These results underscore the lack of the satiating efficiency of empty calories in quickly ingested drinks such as sodas. The increase in perceived fullness that is due solely to the increased viscosity, which is a phenomenon that we refer to as phantom fullness, may be useful in lowering energy intake. This trial was registered at www.trialregister.nl as NTR4573. *Am J Clin Nutr* doi: 10.3945/ajcn.115.129064.

Keywords: energy content, fullness, gastric emptying, MRI, viscosity

INTRODUCTION

An understanding of satiety may help decrease overconsumption. Many factors contribute to satiety from the portion size (1) to orosensory exposure (2, 3). Post-ingestive feedback from the stomach and intestinal tract on the nutrient content (4, 5) and volume (6) also affect satiety.

Gastric feedback affects satiety through stretch receptors via distension, the rate of emptying, and nutrient and energy contents. The increase of feelings of satiety through gastric distension has been shown in previous work (7, 8). Mackie et al. (9) manipulated the gastric emptying rate (GER)[5] with the use of isovolumetric and isocaloric liquid and semisolid meals. It was shown that the condition slowed gastric emptying, which resulted in larger distension and induced enhanced satiety.

Viscosity has been shown to have an effect on satiation and satiety in multiple studies (10–13). However, the literature has been inconsistent when it comes to whether viscosity directly slows gastric emptying. In certain studies, the viscosity did not slow gastric emptying (14, 15); in other studies, the viscosity delayed the GER (16, 17). Hoad et al. (18) reported no difference in gastric emptying between a control guar gum and an intragastric gelling stimulus but did find different fullness scores. The satiating effects of viscosity that have been shown may be related to oral exposure and could be independent of gastric feedback (12).

To our knowledge, Marciani et al. (19) are the only group who studied viscosity and energy density on gastric emptying in one single study. They showed that gastric emptying was slowed by both the viscosity and energy content and concluded that the energy content delays gastric emptying more effectively than does an increased viscosity. Concurrently, they showed that the perceived satiety was affected more by the viscosity. However, the authors stated that further work is necessary with other levels

[1] Supported by the European Union Seventh Framework Programme (FP7/2007–2013) under grant agreement 607310 (Nudge-it).

[2] Supplemental Figures 1S–5S and Supplemental Tables 1S and 2S are available from the "Online Supporting Material" link in the online posting of the article and from the same link in the online table of contents at http://ajcn.nutrition.org.

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[5] Abbreviations used: GER, gastric emptying rate; GE t_{50}, gastric emptying half-time; VAS, visual analog scale.

Received December 16, 2015. Accepted for publication May 4, 2016.
doi: 10.3945/ajcn.115.129064.

of energy and viscosity. More specifically, there are the following 2 areas in which this work can be extended: the energy condition (320 kcal) is compared with shakes with zero energy (excluding dextrose for osmolarity), and the stimuli contain only carbohydrates and fats. It may be important to include the effects of protein (20). More importantly, it may be valuable to compare smaller and larger energy loads with one another to see what the relative delaying effect is of increased energy density. In addition to looking at gastric emptying by measuring changes in the gastric volume, as is commonly practiced, it should prove interesting to also compare gastric emptying per the time unit to further understand gastric emptying dynamics.

Therefore, in this study, we aimed to further elucidate the contributions and effects of viscosity and energy on gastric emptying dynamics and appetite as measured through ratings and intake. We hypothesize that the viscosity and energy would slow gastric emptying. On the basis of studies mentioned previously (18, 21), we expected that a higher energy content would decrease the GER more than would an increased viscosity.

METHODS

Subjects

The subject group consisted of 15 healthy men [mean ± SD age: 22.6 ± 2.4 y; BMI (in kg/m^2): 22.6 ± 1.8]. The healthy adult men were recruited through a website and flyers that were distributed around the campus of Wageningen University. A flowchart of the study is shown in **Supplemental Figure 1S**. Inclusion criteria were as follows: male sex; age between 18 and 35 y; BMI between 18 and 25; self-reported good general health; willingness to comply with study procedures; and willingness to be informed of incidental findings. Exclusion criteria were as follows: unexplained weight loss or gain >5 kg in the past 2 mo; oversensitivity to any of the food items used in the experiment; any reported pathologies relating to the gastrointestinal tract that might influence the results; use of any medications that may influence gastrointestinal function; having any contraindications for undergoing an MRI; not signing the informed consent form; not signing the MRI safety questionnaire before each session; and being employed or studying at the Department of Human Nutrition, Wageningen University.

Potential subjects filled out an inclusion questionnaire to allow them to be screened for eligibility. Subsequently, subjects attended a screening meeting that included measurements of weight and height and an explanation of the study procedures including the MRI procedures. Subjects were unaware of the exact aim of the study; they were only informed that we were investigating the digestive system. We kept the subjects naive to the fact that we varied the energy contents of the shakes.

Before the study, a sample-size calculation was performed. The calculation was based on an estimated effect size with an expected difference ± SD of ∼11 ± 7 min. With statistical significance set at 0.05, which is the significance level in a 2-sided crossover study, a power of 90% would be achieved with 15 subjects. The power calculation was included for review by the Medical Ethical Committee of Wageningen University.

The procedures followed were approved by the Medical Ethical Committee of Wageningen University in accordance with the Helsinki Declaration of 1975 as revised in 2013 (NL48059.081.14). This trial was registered at www.trialregister.nl as NTR4573. Written informed consent was obtained from all subjects.

Design

Subjects came to our facilities 4 times in a randomized 2 × 2 crossover design. Each subject was always scanned at the same time of day. Subjects were offered to drink 1 of 4 shakes, the order of which was based on a scheme that was generated with the use of the website http://www.randomization.com. The scheme was created with the use of balanced permutations. Five randomly selected, willing subjects came for one additional session after completing the 4 sessions to perform a control measurement with the ingestion of 500 mL H_2O.

Session procedures

Subjects were instructed to fast for ≥3 h and to only drink watery fluids in that time and not in the previous 1 h before each session. After arrival, subjects provided baseline appetite ratings and were scanned for baseline stomach contents. After this assessment, subjects exited the scanner and consumed a shake. The shakes were consumed from a blinded cup with a 1-cm diameter straw to allow for the consumption of both the thick and thin shakes through the straw. Subjects were instructed to consume the shake within 2 min. All participants finished the shake within this time. Subjects rated the shakes on a 100-mm visual analog scale (VAS) on liking, sweetness, thickness, and creaminess. Subjects were then positioned in the scanner, and stayed there for 90 min, gave subjective ratings via the intercom, and underwent a gastric MRI scan every 10 min (for an overview of the session, see **Figure 1**). At the end of the session, the subjects were offered a sandwich meal of which food intake was recorded.

Treatments

The ingredients for the shake were cream (AH Basic; Albert Heijn BV), dextrin-maltose (Fantomalt Nutricia), vanilla sugar (Dr.Oetker), whey powder (Whey Delicious Vanilla; XXL Nutritions), and water. Fiber in the form of locust bean gum was added to the shakes (1 g for the thin shakes, 20 g for the 100-kcal shake, and 10 g for the 500-kcal shake) to manipulate the viscosity. The viscosity was visibly affected. Rheology measurements were performed in line with previous work (10). The flow behavior is shown in **Supplemental Figure 2S**. Energy was manipulated by differing grams of added ingredients. Macronutrients of the shake were combined to reflect a mixed meal in which 50% of the energy came from carbohydrates, 30% of the energy came from fat, and 20% of the energy came from protein (the composition is shown in **Table 1**). Shakes were mixed in a container with an internal whisking ball for ∼30 s. All shakes were prepared ∼15 min before intake and offered at 20°C.

Table 1 also gives an overview of the liking, creaminess, sweetness, and thickness VAS ratings. Liking was significantly different between shakes with different energy loads. Creaminess was significantly higher for both the thick shake and the 500-kcal condition. Sweetness was significantly higher for the 500-kcal shake. The viscosity and energy significantly increased the reported thickness. The perceived thickness was greater for the

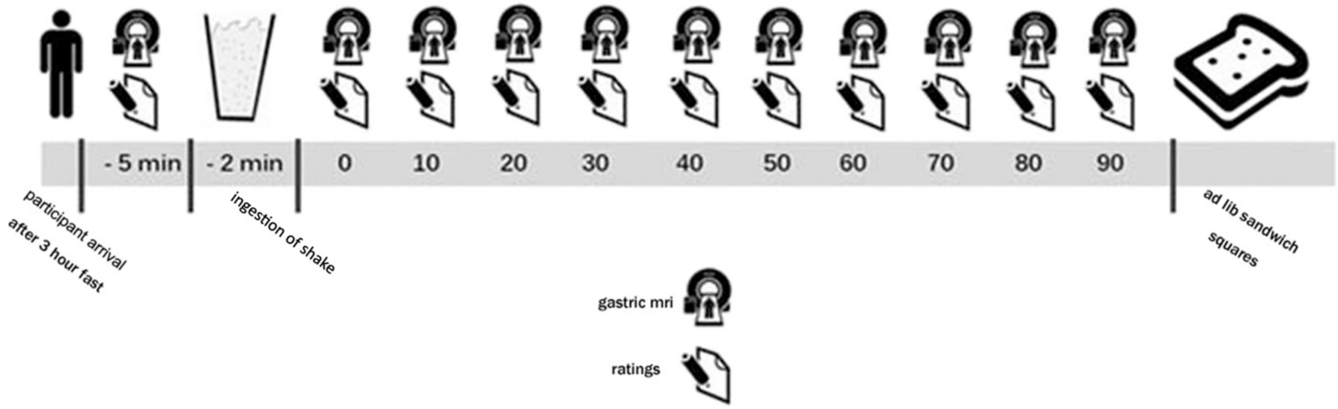

FIGURE 1 Overview of one experimental session for one participant.

high-viscosity condition than for the low-viscosity condition. In addition, a greater energy load increased the perceived thickness both in the low- and the high-viscosity conditions.

Outcome subjective appetite ratings

Subjects rated hunger, fullness, prospective consumption, desire to eat, and thirst on a 100-mm VAS at baseline (i.e., before intake of the shake). After ingestion, these ratings were obtained orally every 10 min over the scanner intercom system and were orally scored by the subject from 1 to 100 points (22).

Gastric volume

Subjects were scanned with the use of a 3-T Siemens Verio MRI scanner (Siemens AG) with a T_1-weighted spin-echo sequence (HASTE; 24 6-mm slices, 2.4-mm gap, 1.19 × 1.19-mm in-plane resolution; Siemens AG) and a breath-hold command on expiration to fixate the position of the diaphragm and the stomach. The duration of one scan was ∼19 s. Syngo fastView MRI software VB17 (http://www.healthcare.siemens.com/medical-imaging-it/syngo-special-topics/syngo-fastview; Siemens AG) was used to manually delineate the gastric content on every slice (**Figure 2**). The gastric volume at each time point was calculated by multiplying the surface area of the gastric content per slice with the slice thickness, including the gap distance, and summed over the total slices showing the gastric content. Gastric emptying was defined as the decrease in gastric content in milliliters over time.

Food intake

After 90 min, subjects were offered a 500-mL bottle of water and a surplus of ham and cheese sandwich squares. The serving consisted of 20 squares with the message that more was available if required; one square was ∼312 kJ/75 kcal. Participants were instructed to eat until they were pleasantly satisfied. The number of sandwich squares eaten was recorded and used to calculate intake.

TABLE 1
Energy contents and nutrient compositions of the shakes per 100 g and viscosity and sensory characteristics

	Thin 100 kcal	Thick 100 kcal	Thin 500 kcal	Thick 500 kcal
Protein powder, g	4.5	3.9	12.9	12.5
Cream, g	7.5	6.6	21.6	20.8
Dextrin-maltose, g	7.9	6.9	22.8	22
Vanilla sugar, g	6	5.2	3.4	3.3
Locust bean gum, g	0.7	13.1	0.5	4.1
Water, g	73.4	64.3	38.8	37.3
Total grams	100	100	100	100
Energy,[1] kJ	84	84	418	418
Carbohydrates, g	2.4	2.4	12	12
Monosaccharides and disaccharides	0.4	0.4	2.1	2.1
Fat, g	0.6	0.6	3	3
Protein, g	1.2	1.2	6	6
Fiber, g	0.5	4	0.5	2.5
Pleasantness[2]	35.7 ± 4.3[3]	30.3 ± 4.5	65.5 ± 3.7	61.9 ± 4.2
Creaminess[2]	27.9 ± 5.2	60.8 ± 5.6	48.6 ± 5.1	71.1 ± 3.1
Sweetness[2]	37.0 ± 6.1	30.2 ± 3.9	67.1 ± 5.4	71.5 ± 3.1
Thickness[2]	14.3 ± 2.6	72.7 ± 4.1	30.8 ± 4.2	53.5 ± 4.9

[1]Nutrient composition of shakes resembled a mixed meal with 50% of the energy load coming from carbohydrate, 30% of the energy load coming from fat, and 20% of the energy load coming from protein.

[2]Rated on a 100-mm visual analog scale.

[3]Mean ± SEM (all such values).

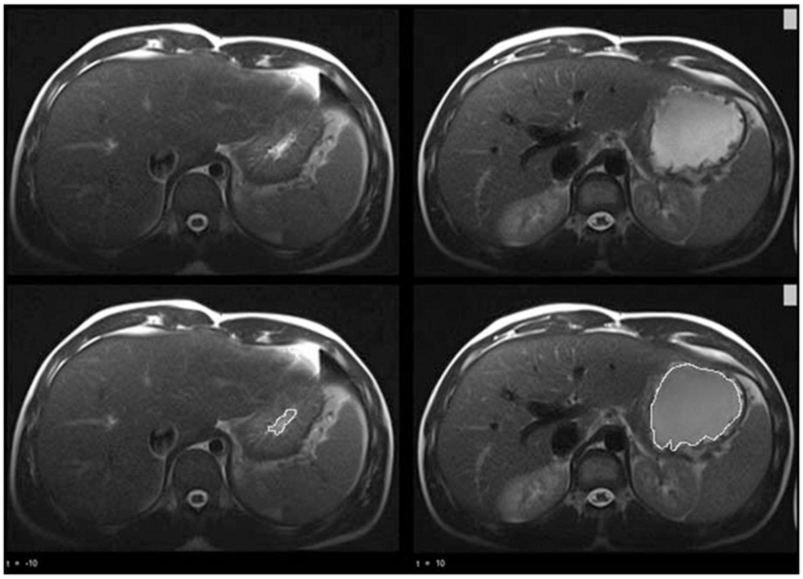

FIGURE 2 Transversal slice at the height of the liver before ingestion (left) and 10 min after ingestion (right). Bottom scans have surface areas of the gastric contents delineated in white. The surface area was used to calculate the gastric volume at the moment of a scan.

Control session with water

A subset of 5 participants returned for a fifth session in which they underwent the same procedure with 500 mL H_2O instead of a shake. Because of the rapid emptying of the water, the scanning time for those sessions was limited to 25 min after ingestion. Results, including the water control, are shown in **Supplemental Figures 3S** and **4S**.

Statistical analyses

The gastric emptying half-time (GE t_{50}) was calculated according to the linear exponential model for gastric emptying that was developed on the basis of earlier models in Zurich (23, 24). The data were fitted to the model, and the GE t_{50} was extracted with the use of R software (version 3.2.2; R Foundation for Statistical Computing).

The GER was calculated by subtracting gastric volumes to the amount of millimeters that was emptied in the 10 min between scans. The AUC over the course of 90 min was calculated for subjective ratings. The AUC was calculated with the use of Graphpad Prism 5 software (Graphpad Software) according to the trapezoidal rule.

All data were quantitative. Data are expressed as means ± SDs unless otherwise stated. Testing for differences between treatments for gastric emptying was done with the use of a general linear mixed model of GE t_{50} scores, for GER with the use of a general linear mixed model of the emptied amounts, and for appetite scores with the use of a general linear mixed model of the AUC. The energy load and viscosity were included as fixed factors, and subjects were included as a random factor in the model. For the subjective appetite ratings analysis, baseline measurements were included as a covariate (25). Analyses were performed with the assumption of a first-order autoregressive covariance structure. Post hoc Šídák-adjusted tests were performed to further examine the main effects. Statistical analyses were performed with IBM SPSS 20 software (IBM). The significance level was set at $P = 0.05$.

RESULTS

Gastric emptying

Figure 3 shows the gastric volume over time of the different treatments. The thin 100-kcal shake had the lowest GE t_{50} of 26.5 ± 3.0 min (95% CI: 11.9, 41.4 min), which was followed by the thick 100-kcal shake with a GE t_{50} of 41 ± 3.9 min (95% CI: 26.4, 55.9 min) and the thin 500-kcal shake with a GE t_{50} of 69.5 ± 5.9 min (95% CI: 54.9, 84.4 min), and the thick 500-kcal shake had the highest GE t_{50} of 81.9 ± 8.3 min (95% CI: 67.3, 96.8 min).

For the GE t_{50}, there was a significant effect of the viscosity ($P = 0.006$, $F = 8.4$) and energy content ($P < 0.001$, $F = 81.8$). Estimated means were closer together for the viscosity (100 kcal: 48.2 ± 5.4 min; 500 kcal: 61.6 ± 5.4 min) than for the energy

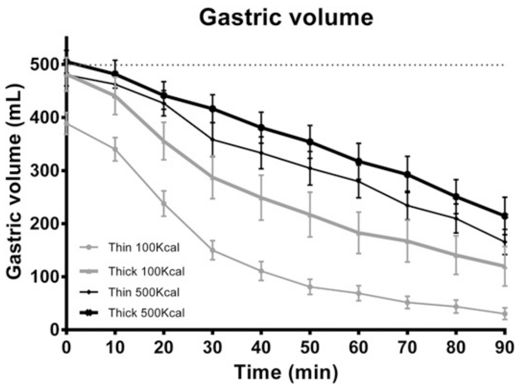

FIGURE 3 Mean ± SEM gastric volumes measured by multiplying the slice surface area with the summed slice distance and thickness. From the emptying curve of the individual subject, the gastric emptying half-time was extracted, and the mean gastric emptying half-time was calculated per treatment (thin 100 kcal: 26.5 ± 3.0 min; thick 100 kcal: 41 ± 3.9 min; thin 500 kcal: 69.5 ± 5.9 min; and thick 500 kcal: 81.9 ± 8.3 min). A mixed model analysis showed that the viscosity significantly increased at 50 min ($P = 0.006$, $F = 8.4$) as did the energy content ($P < 0.001$, $F = 81.8$). Post hoc tests showed that all pairwise comparisons were significant with the exception of the thin and thick 500-kcal shakes. $n = 15$.

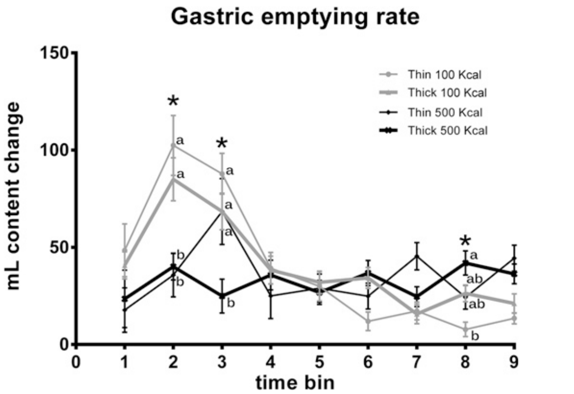

FIGURE 4 Mean ± SEM volume differences between scans per shake. Each time bin corresponds to 10 min and shows the difference between the determined gastric content at the beginning and end of the 10 min (in mL). *The mixed model analysis showed significant differences in bins 2, 3, and 8. Below the *x* axis, significant pairwise comparisons are shown (different letters denote significant differences; the order of the letters follows the legend. **Supplemental Table 2S** shows all pairwise comparisons and *P* values. *n* = 15.

load (thin: 33.9 ± 5.4 min; thick: 75.8 ± 5.4 min). Post hoc tests showed that the GE t_{50} was significantly higher under both the low-viscosity condition ($P < 0.001$, $F = 43.0$) and the high-viscosity condition ($P < 0.001$, $F = 38.9$). The gastric emptying time was significantly higher because of an increased viscosity under the low–energy-load condition ($P = 0.033$, $F = 4.8$) but not under the high–energy-load condition ($P = 0.065$, $F = 3.6$). Significant effects of increasing the energy load on the GE t_{50} were an increase of 42.9 min under the thin condition and of 40.9 min under the thick condition. The viscosity increased the GE t_{50} by 14.5 min in the 100-kcal condition.

The curve for the GER is shown in **Figure 4**. In **Supplemental Table 1S**, the emptying rate (kcal/min) for each time bin is shown. Significant differences were shown in bins 2, 3, and 8, of which bin 2 showed the largest mean emptying differences (thin 100-kcal shake: 102 mL; thick 100-kcal shake: 85 mL; thin 500-kcal shake: 35mL; thick 500-kcal shake: 40 mL). The differences between the 100- and 500-kcal shakes were significant. In **Supplemental Table 2S**, complete pairwise comparisons of the 4 shakes/bin, including *P* values, are shown.

Appetite ratings

An overview of all AUC mean values and *P* values for the main effects are shown in **Table 2**. Hunger was not significantly affected by the viscosity or energy load. Fullness ratings over time are shown in **Figure 5**. The AUC for fullness was significantly higher after increasing the viscosity ($P = 0.007$, $F = 8.1$; estimated means of the AUC were 3976.3 ± 264.6 under the thin condition and 4718.6 ± 264.6 under the thick condition). The effect of increasing the viscosity on fullness was an increase of 984.2 points on the AUC. For prospective consumption, there was a significant interaction effect ($P = 0.038$). Increases of prospective consumption ratings of the energy load under the high-viscosity condition ($P = 0.043$, $F = 4.4$) and increases of the prospective consumption ratings of viscosity under the high–energy-load condition ($P = 0.001$, $F = 13.0$) were significant. The effect of increasing the viscosity was an increase of 1129.9 points on the AUC. The effect of increasing the energy load was an increase of 654 points on the AUC. For the desire to eat, there was a significant interaction effect as well ($P = 0.026$). The post hoc analysis showed that desire-to-eat ratings were significantly decreased by increasing the viscosity but only under the high–energy-load condition ($P = 0.018$, $F = 6.1$). The effect of increasing the viscosity was an increase of 1210.3 points on the AUC. Curves for hunger, prospective consumption, and desire to eat are shown in **Supplemental Figure 5S**.

Ad libitum intake

Participants consumed ∼7 sandwich squares after the session, which corresponded to 1.75 ham and cheese sandwiches. There were no significant differences in intakes of sandwiches between treatments (effect of viscosity: $P = 0.190$, $F = 1.8$; effect of energy load: $P = 0.804$, $F = 0.062$) (**Table 3**).

DISCUSSION

In the current experiment, we studied the effects of viscosity and energy load on gastric emptying and satiety. The increase of the energy load led to slower gastric emptying over time; the increase of viscosity only significantly slowed the emptying under the low–energy-load condition. The GER was very similar for the two 100-kcal conditions despite the substantial difference in viscosity. The viscosity significantly changed the appetite ratings, whereby fullness scored higher, and the desire to eat scored lower.

In confirmation of our hypothesis, we showed that gastric emptying of a low energy load was quicker than that of a stimulus with a higher energy load. This result corresponds with the finding of a study of Marciani et al. (19). In addition, gastric

TABLE 2
Appetite-rating AUCs over the course of 90 min (*n* = 15)[1]

	Shake				*P*		
Subjective response	Thin 100 kcal	Thick 100 kcal	Thin 500 kcal	Thick 500 kcal	Viscosity	Energy load	Viscosity × energy load
Hunger	4487 ± 1645	4306 ± 1624	4573 ± 1253	3797 ± 1723	0.071	0.544	0.065
Fullness	4063 ± 1390	4774 ± 1151	4108 ± 1056	5071 ± 1109	0.007	0.599	0.357
Prospective consumption	5258 ± 1316[a]	4851 ± 1360[a]	5346 ± 1143[a]	4299 ± 1418[b]	0.005	0.422	0.038
Desire to eat	5122 ± 1585[a,b]	4691 ± 1608[a,b]	5392 ± 1554[a]	4206 ± 1725[b]	0.248	0.633	0.026
Thirst	4375 ± 1551	4776 ± 1653	4373 ± 1629	4531 ± 1641	0.124	0.877	0.122

[1]All values are means ± SDs. In accordance with the trapezoidal rule, AUCs were calculated per session over the course of 90 min/subject and the mean was calculated. *P* values were determined with the use of a general linear mixed model analysis of main effects. If an interaction was significant, post hoc Šídák tests were performed. Significant differences are shown with the use of different superscript letters noted after AUC scores.

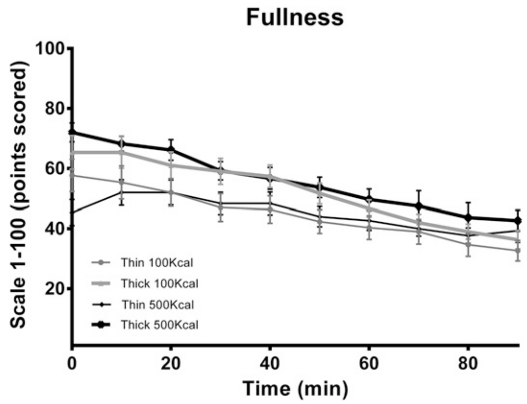

FIGURE 5 Mean ± SEM fullness scores shown per time point. t = 0 was the moment the stimulus was consumed. n = 15.

emptying was delayed by increasing the viscosity, albeit less effectively (21). Our findings indicate that the difference in gastric emptying between a thin low-energy fluid and a thick low-energy fluid can be completely explained by the quicker drainage within the very first moments after consumption. If we correct for the draining in the beginning by looking at the GER per 10 min, the viscosity has little to no effect.

It is known that gastric sieving of water occurs, which can be mitigated by blending the water with the stimulus (26). The blending of a stimulus may influence both the energy load sensed in the duodenal of the emptied gastric content as well as the viscosity of the content in the stomach. Because of this phenomenon, it remains unclear whether this blending slows emptying by increasing the energy load, increasing the viscosity, or both. Our research showed that increasing the energy load by a factor 5 from 100 to 500 kcal slowed gastric emptying significantly more than did increasing the viscosity by a much larger factor. Therefore, our results indicate that the gastric sieving effect is due to the sieved fluid, namely water, having a low caloric content. In the blended condition, the fluid fraction is much more caloric. These calories, regardless of viscosity, can be the cause of delayed emptying.

The thin 100-kcal shake in our experiment showed an ∼100-mL lower starting volume than that of the other 3 shakes. This lower starting volume was also apparent in the water control treatment. Approximately 100 mL seeped through before the gastric content was retained. The slope of the subsequent emptying curve seemed very similar between the 100-kcal thin and thick shakes. This relation was also reflected in the GERs, which appeared to be very similar for the shakes with equal energy loads. This result suggests that, in our experiment, the GER was not driven by viscosity and that previously reported differences (27) might have been due to gastric seeping of the first milliliters of a stimulus, which is both thin and contains a low energy load. This seeping through of the first 100 mL may also have been an important effect that confounded results in studies that used indirect methods to assess differences in gastric emptying dynamics such as the plasma acetaminophen concentration or C^{13} labeling. Additional research in this area is warranted to establish the effects of viscosity and energy density on this initial seeping through of gastric contents. Furthermore, it may be important in the future to measure the gastric volume during ingestion as well to catch the content before it seeps through.

It has been suggested, and it seems logical, that slower gastric emptying increases feelings of satiety (4). Clegg et al. (4) showed a larger AUC for fullness after the consumption of a smooth soup than after the consumption of a chunky or solid meal. They concluded, on the basis of their gastric emptying data, that this effect was due to the longer gastric distension by the soup. Our results may suggest an alternative explanation for the satiating power of soup. We showed that subjective ratings were more heavily influenced by viscosity than they were by the energy load, which was most apparent in the self-reported fullness. It would be expected that perceived fullness follows the gastric volume quite naturally. However, we showed higher ratings for the thick 100-kcal shake than for the 500-kcal thin shake although the former emptied much more quickly. For example, we showed that both thick shakes and both thin shakes had comparable fullness ratings at 40 min after ingestion; however, mean scores for the thick shakes were only ∼8 points lower on a 100-point scale. When we looked at the gastric content at 40 min, ∼350 mL was retained in the stomach after consumption of the 500-kcal shake, but 250 mL was retained after consumption of the 100-kcal thick shake, and only 110 mL was retained after consumption of the thin shakes. Thus, the thin shakes yielded similar fullness ratings although the stomach was filled with 350 mL in one condition and 110 mL in the other condition.

Concurrently, we showed low fullness ratings without the postprandial peak of the other stimuli for the thin 500-kcal shake. This well-known effect is often referred to in popular science as the "empty calories" in sodas. Not only did we show an empty calories effect of the thin 500-kcal shake, but in contrast, we also showed that there was high fullness even when the shake was emptied quickly. Thus, increasing the perceived thickness created a kind of phantom fullness, whereby there was a perceived feeling of fullness that was is not congruent with the actual gastric content. This hypothesis has been supported by results from work with low-calorie foams (28), which reduced the appetite.

Thus, the link between subjective fullness and gastric fullness may be weaker than it sometimes has appeared in previous work (29). The importance of effort and mouth feel has been shown in multiple studies (30). Hunger is suppressed more or for a longer period (31, 32), intake is reduced (3, 12), and, through longer mastication, satiety is increased (33, 34). We propose that taste and mouth feel are perhaps contributing factors to subjective

TABLE 3
Intake of sandwich squares 90 min after shake intake (n = 15)[1]

	Thin 100 kcal	Thick 100 kcal	Thin 500 kcal	Thick 500 kcal
Sandwich squares consumed,[2] n	8.40 ± 4.91	6.40 ± 4.61	7.27 ± 3.80	7.13 ± 4.31
Energy of sandwich squares consumed, kJ	2618 ± 1529	1995 ± 1438	2266 ± 1186	2222 ± 1345

[1]All values are means ± SDs.
[2]Mixed model analysis yielded no significant differences between treatments.

feelings of fullness. This possibility may offer an alternative explanation to findings in earlier studies that concluded that greater satiety was caused by delayed gastric emptying (9), both of which may have resulted from a greater oral and sensory exposure of viscous stimuli. The importance of the perception in the mouth was underlined in a study that showed that gastric emptying was only slowed down when stimuli were administered orally and not when they were administered intragastrically (35). A design that used sham feeding showed that the oral exposure through sham feeding was not enough to delay gastric emptying (36). To further understand this outcome, similar paradigms with the inclusion of hormone-concentration measurements would be highly interesting. If taste and mouth feel contribute to fullness feelings as we propose, the manipulation of mouth feel should change hormone concentrations such as those of cholecystokinin.

Research that uses an MRI requires a supine position. In our study, subjects remained completely stationary in their supine position for 90 min. This supine position meant that the gastric content flowed slower through the pyloric sphincter because gravity did not propagate the flow as effectively as it would in a standing or sitting position. Our observed emptying may have been slower than it would have been in a more-natural position (37), which meant that appetite scores and calculated emptying times may not transfer directly to the natural situation because of the overestimation of absolute effects. A second effect of the supine position was that the observed emptying may have represented more-active emptying by gastric contractions.

In conclusion, gastric emptying is slowed by increases in both the energy load and the viscosity. However, increasing the energy load is the most important factor. Viscosity loses its retarding effect if the energy load is increased to a meal size of 500 kcal. This effect indicates that the viscosity may not affect satiety and satiation through delaying gastric emptying. We showed significant changes in subjective ratings that were due to viscosity, which indicated that increased satiation and satiety are affected by viscosity through mouth feel and oral exposure. Moreover, subjects showed no tendency to compensate for the caloric intake during the meal afterward. A thick shake containing 100 kcal will yield higher fullness ratings and lead to similar intake when compared with a thin shake containing 500 kcal. We may find use for this phantom-fullness effect (i.e., a sense of fullness and satiation caused by the taste and mouth feel of a food irrespective of its caloric content). Thick low-caloric liquid meals may leave people feeling fuller and more satiated, thereby preventing compensatory overconsumption afterward.

We thank Arjen Riemsma for his invaluable help with the development of the MRI protocol. We also thank Maryan Schrover for her help with the language of the manuscript.

The authors' responsibilities were as follows—GC: conducted the research, performed the variable extraction, and wrote the manuscript; GC and MM: performed the statistical analysis; MM, CdG, and PAMS: provided feedback; PAMS: had primary responsibility for the final content of the manuscript; and all authors: designed the study and read and approved the final manuscript. None of the authors reported a conflict of interest related to the study.

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