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Oatmeal particle size alters glycemic index but not as a function of gastric emptying rate

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Abstract

Scope: The aim of this study was to determine the extent to which oat particle size in a porridge could alter glucose absorption, gastric emptying, gastrointestinal hormone response and subjective feelings of appetite and satiety.

Method and results: Porridge was prepared from either oat flakes or oat flour with the same protein, fat, carbohydrate and mass. These were fed to eight volunteers on separate days in a crossover study and subjective appetite ratings, gastric contents and plasma glucose, insulin, and gastrointestinal hormones were determined over a period of three hours. The flake porridge gave a lower glucose response than the flour porridge and there were apparent differences in gastric emptying in both the early and late post prandial phases. The appetite ratings showed similar differences between early and late phase behavior.

Conclusions: The structure of the oat flakes remained sufficiently intact to delay their gastric emptying leading to a lower glycemic response, even though initial gastric emptying rates were similar for the flake and flour porridge. This highlights the need to take food structure into account when considering relatively simple physiological measures and offering nutritional guidance.

New and Noteworthy

The impact of food structure on glycemic response even in simple foods such as porridge is dependent on both timing of gastric emptying and the composition of what is emptied as well as duodenal starch digestion. Thus structure should be account for when considering relatively simple physiological measures and offering nutritional guidance.

Keywords

Oats; glycemic response; particle size; gastric emptying, appetite

1. Introduction

The food industry is faced with the task of producing highly palatable foods that meet consumer preferences and comply with their nutritional needs. However, the overabundance of very nutritious food has brought with it a number of challenges associated with adverse health outcomes. Of special concern is the dramatic increase in obesity and metabolic diseases. Therefore now, more than ever we need to understand the mechanisms through which rates of nutrient release may be controlled, affecting physiological responses to food as well as sensations of appetite and satiety. The way that dietary components and food structure modify digestion kinetics may reveal foods with the potential to reduce risk factors associated with metabolic diseases such as type 2 diabetes, e.g. hyperglycemia and elevated blood pressure.

Recent research indicates that oats (*Avena sativa*) contain bioactive components that have a range of positive health benefits, including effects on lipidemic and glycemic control (14, 31), as well as satiety (3). Soluble fiber may promote satiety, by slowing down digestion resulting in increased gastric retention and feelings of fullness (15). The presence of soluble fiber has also been shown to alter the secretion of gastrointestinal hormones (4) and aid body weight regulation (33).

During the digestion of food there are two modes of gastric emptying. Firstly by eroding the solid bolus of food in the stomach from the outside, where the food has been most exposed to acid and enzymes. The chime may then be squeezed through the pylorus into the duodenum if the particle size is sufficiently small (22, 23). When the gastric contents are more fluid or semi-solid (e.g. soup or porridge), emptying occurs primarily during periods of quiescence in antral pressure activity and, by implication, in antral contractile activity (13) and thus may empty from the center of the stomach, a zone that has not been subjected to significant pH change or exposed to gastric enzymes (29). In the antrum, selective 'sieving' permits the rapid passage of liquids and smaller food particles while the larger particles are retained for further processing, although this is effected by the viscosity of the gastric

contents (24). The size cut-off means that particles larger than about 3 mm (17) tend to be retained longer, although not indefinitely (34). The rate at which food is emptied from the stomach depends on a number of factors but one is the energy density of the food (11, 12). As far back as the 1970s it was shown that energy density has an inverse effect on gastric emptying. However, in addition, the rheological properties of the gastric content play an important role on gastric processing (9) and emptying rate. Although both are important, increasing the viscosity is considered less effective than increasing the energy density in slowing gastric emptying (7).

A number of foods have traditionally been eaten because they are perceived as healthy, and this includes oat porridge. However, studies have shown that the way that the oats are processed has a strong influence on glycemic index (36). In particular, the modern trend towards quick cook oats is likely to have a significant effect on the glycemic index of the final product. It is not clear, though, whether this difference is a result of alterations in gastric residence time or intestinal starch hydrolysis. Indeed given the high beta-glucan content of oats it could be that release of this polymer significantly alters intestinal viscosity, or has a similar influence on gastric residence time because although energy density affects gastric emptying, it is also effected by viscosity (7). The milling process of oat flakes increases the accessibility of nutrients and fiber, including beta-glucan, and this may influence gastric emptying dynamics and glycemic response. Thus, our study investigated the effect of oat grain processing upon gastric emptying rates, glycemic response and satiety. Study participants consumed two isocaloric porridges prepared from finely milled oats and flaked oats, and MRI imaging was used to study gastric volumes and layering. Subjective feelings of appetite and satiety were recorded, as well as levels of blood glucose, insulin and GI hormones. The overall aim was to understand how food structure is involved with some of the mechanisms that regulate hunger, appetite and satiety. Our hypothesis was that greater release of starch and soluble fiber from the finely milled porridge would generate a higher viscosity in the stomach than the flaked porridge. In combination with the more effective

nutrient release from the finely ground porridge this would lead to a lower glycemic response, slower gastric emptying and greater feelings of fullness for longer.

2. Materials and Methods

2.1 The meals

The two meals used in this crossover were based on the same porridge recipe. The composition of the two meals is given in Table 1. Both oat samples had the same composition as they were produced from the same batch of Norwegian Belinda oats. The oat flakes were of commercial quality, provided by Lantmännen Cerealia, Moss, Norway. The oat flakes were milled into flour using a hammer mill (Retsch ZM 200, Dale, Norway) with a 0.5 mm screen. The β-glucan content of the oats was 4.52 g / 100 g dry weight as determined by an enzymatic method using a mixed linkage beta-glucan assay kit from Megazyme (Megazyme International, Bray, Ireland). Oat flake or oat flour porridge was prepared on the morning of the study using the following protocol: Skimmed milk, water and margarine were gently heated until the margarine melted. Then either oat flakes or oat flour were added and well mixed. The mixture was brought to the boil (constant stirring), then added sugar and salt, and boiled for 1 minute. The porridge was then transferred to an insulated container and transported (approx. 10 minutes) to a room set aside for its consumption, adjacent to the MRI facility.

2.2 Imaging of gastric contents

The gastric contents of the volunteers was determined using a conventional 3T magnetic resonance imaging (MRI) scanner (GE Discovery MR750w). Imaging used a FIESTA (Fast Imaging Employing Steady-state Acquisition) protocol developed to scan the stomach in a breath-hold of the order of 15-20s depending on the fullness of the stomach (TR/TE 3.73/1.19ms, Field of view 450 mm, matrix 512 x 512, slice thickness 5 mm). This yields contiguous 5mm axial slices through the stomach enabling calculation of total stomach

volume. Both transverse and coronal images were acquired in order to ensure that the gastric volume could be accurately defined. Total volumes of gastric contents (excluding gas) and the nature of layers formed as a result of sedimentation were determined at each time point using freehand tracings of the region of interest around the stomach contents for each 5mm thick slice and from this the total stomach volume was calculated using Image-Pro Plus v7.1 software (Media Cybernetics inc, San Diego, USA) (20). This involved assessment of the position of the pylorus. Each set of scans took about 5 minutes and between scans the volunteers remained seated upright close to the scanner. From the variation of the gastric volume with time we deduced an apparent emptying rate, which provides the estimated rate at which the food emptied from the stomach, due to the inhomogeneous distribution of the food material inside the stomach and because of the simultaneous addition of gastric secretion.

2.3 Visual analogue scales

We assessed volunteer satiety with a self-reported visual analogue scale technique (35). Before the meal and at specific time intervals post-meal as given in Table 2, the volunteers completed a five question satiety questionnaire with a visual-analogue scale (VAS) for each of the following questions: (1) “How hungry are you?” (2) “How full do you feel?” (3) “How satisfied do you feel?” (4) “How big is your desire to eat?” (5) “How thirsty are you?”. The analogue scores for each question were then converted to numeric scores based on the following: 1. 1=“not at all hungry” 10=“very hungry”; 2. 1=“not full at all”, 10=“very full”; 3. 1=“not satisfied at all”, 10=“very satisfied”; 4. 1=“no desire to eat at all”, 10=“very big desire to eat”; 5. 1=“not thirsty at all”, 10=“very thirsty”. The individual participant data were normalized by subtracting the mean value and dividing by the standard deviation of each time course. The data are presented as the difference from baseline and show the mean +/- the standard error in the mean.

2.4 Determination of glucose, insulin and GI hormones

At the start of each study session volunteers were fitted with a cannula so that blood could be drawn periodically. At each required time point 4ml of blood was drawn and stored on ice for less than two hours before being centrifuged. Blood was collected into tubes (Vacutainer K2 EDTA, Becton Dickenson, USA) containing 170.9 µl (2000 KIU) of aprotinin (Sigma-Aldrich, UK) and after centrifugation for 10 minutes at 1500 x g and 4 °C the plasma was removed and stored in pre-labelled tubes at -80 °C. The plasma analysis was performed by the Core Biochemical Assay Laboratory of Cambridge University Hospitals. The plasma was analyzed for insulin, GIP (glucose-dependent insulinotropic peptide*)* and GLP-1 (*Glucagon-like peptide 1)* by Diasorin Liaison XL auto analyzer. The insulin concentrations were determined using a one-step chemiluminescence immunoassay also from Diasorin (Diasorin S.p.A, 13040 Saluggia (VC), Italy). The GLP-1 and GIP concentrations were determined using electrochemical luminescence immunoassay kits from MesoScale Discovery (Gaithersburg, MD, USA). The plasma samples were also analyzed for glucose using a Randox Datona+ (Randox Laboratories Ltd, Crumlin, UK) and a colorimetric GL 8318 glucose kit.

2.5 Determination of viscosity and available β-glucan during in vitro digestion

A simulated digestion model (28) was used to digest porridge samples (2 g) in duplicates. Pepsin (P7000 from porcine gastric mucosa (EC 3.4.23.1), Sigma-Aldrich, St. Louis, US), pancreatin (P1750 from porcine pancreas, Sigma-Aldrich, St. Louis, US) and bile salts (B8381 bile from bovine and ovine, Sigma-Aldrich, St. Louis, US) were used at concentrations of 2000 U/mL, 100 U/mL (based on trypsin activity) and 10mM, respectively, in the final digestion mixtures. The digestion was performed in 50mL centrifuge tubes placed horizontally in a shaking incubator (Innova 40, Incubator Shaker Series, New Brunswick Scientific, Edison, New Jersey, US) at 175 rpm and 37˚C. Incubation in the intestinal phase was 2h, after which the samples were centrifuged at 4000 rpm for 10 min (Heraeus Multifuge

4 KR). An aliquot of the supernatant was boiled for 5 min, diluted, filtered through a 0.8μm syringe filter and injected into a HPSEC system with calcofluor detection to determine β-glucan M_w as previously described (30). The β-glucan concentrations were calculated from the area under the chromatographic peak using β-glucan standards of known concentration as reference. The viscosity of the supernatants was measured at constant shear ($10s^{-1}$) using a Physica MCR 301 rheometer (Anton Paar, Stuttgart, Germany) fitted with a double gap geometry (DG26.7).

2.6 Methodology

The crossover study was designed to assess differences in gastric emptying, satiety indicators and levels of glucose, insulin and GI hormones glucose-dependent insulinotropic peptide (GIP) and glucogon like peptide 1 (GLP-1). The study included only male volunteers aged between 37 and 53 and with a BMI between 23 and 30. The mean age of the cohort was 46+/- 6 and the mean BMI was 26.4 +/- 1.7. The clinical details of the participants are given in Table 2. All 8 volunteers recruited to the study were apparently healthy and provided written informed consent before taking part in the study, which was approved by an NHS research ethics committee (Approval 15/SW/0165). Each volunteer attended the study center on two occasions, at least 7 days apart consuming a different meal on each occasion. The order in which the meals were consumed was randomly allocated. All volunteers were able to consume all of the test meals within 5 minutes.

On each study day volunteers were asked to fast overnight, with the last consumption of a meal prior to 22:00 the previous day to the study. They were allowed to drink as much water as they needed but only until 07:00. After this time no further consumption was allowed. The experimental protocol was started between 08:30 and 09:00, which corresponds to the first time point in Table 3. After initial formalities each volunteer had a cannula inserted into an arm ready for blood drawing. They then underwent the first MRI scan, a 4 ml sample of blood was drawn and they were asked to complete a VAS questionnaire (baseline

measurements). The volunteer consumed the meal, allocated at random. Immediately after the meal has been consumed the second MRI scan was performed with subsequent scans being undertaken as laid out in Table 3. The volunteers were asked to repeatedly complete a VAS satiety questionnaire and have a 4 ml sample of blood drawn and the timing for these are also given in Table 3.

2.7 *Statistics*

The study was powered based on the primary outcome, glycaemic response, which in healthy participants is most significantly shown with insulin. Using the data from a previous study (32) as a guide, in order to see a significant difference ($P<0.05$) of at least 18 pmol/L (106 pg/mL) insulin between treatments, the current study requires 8 volunteers (power=95%). The data are multivariate by nature, which calls the need to be analysed as such. For overview and validation multivariate data analysis using Partial Least Squares Discriminant Analysis (PLS-DA) (2) were performed with product type (flakes vs flour) as response variable. The features were standardized to unit variance. The PLS-DA model was performed by Unscramble (version 10.3, Camo Software) and plotted in the setup using the data programming language R (http://www.r-project.org/ Version 3.2.2). Validation of the model is given as percentage of correctly classified response (Flour, Flakes) in a cross validation test where one sample at a time is left out from the calibration and used for the validation. The results are presented first for one feature at the time using error bars as guidelines.

3. Results

The primary aim of the study was to determine whether oat porridge produced from flaked oats gave a different glycemic response and remained in the stomach for longer than porridge made from oat flour. Participants were fed 264 g of porridge along with 175 mL of

water making a total of ~440mL, which was consumed in less than ten minutes. Analysis of the MRI images yielded the volume of gastric chyme for all participants as a function of time. This data, shown in Figure 1, indicates an initial gastric volume slightly higher than the meal volume after 5 minutes, which is most likely due to the fasting secretion present before the meal was consumed. The data demonstrates very little difference between the two meals. However, towards the end of the gastric cycle it is clear that more of the flakes remained in the stomach.

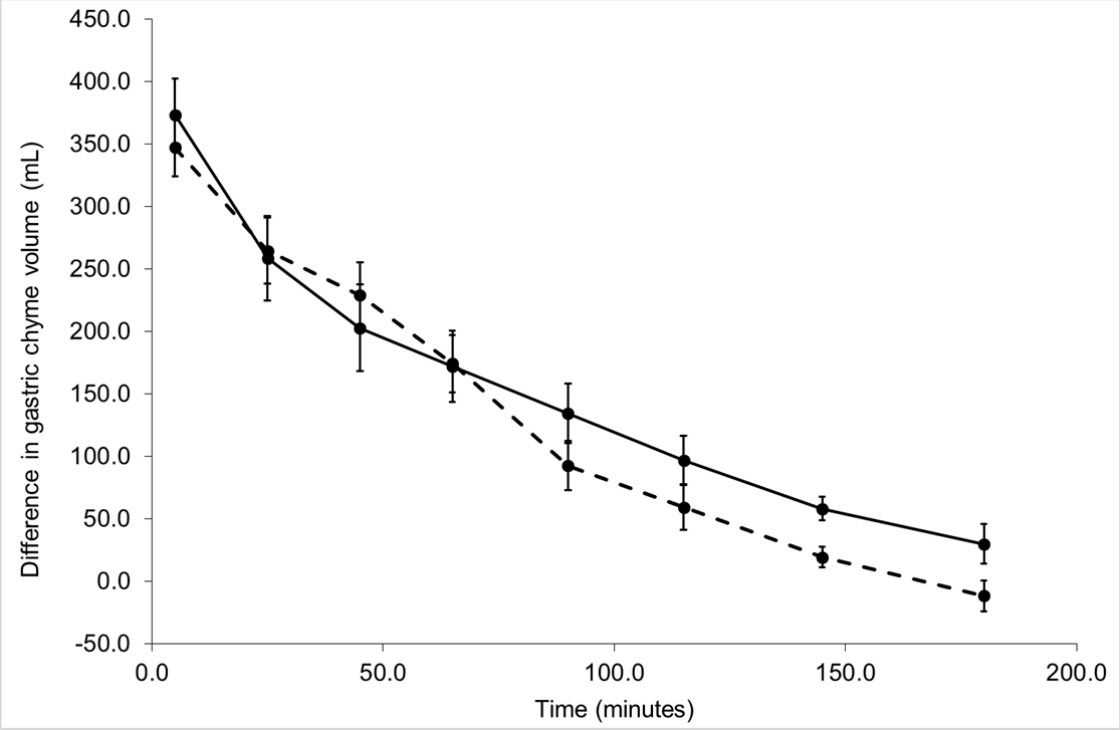

Figure 1: Difference in volume of gastric chime above baseline after consumption of porridge made from either oat flakes (continuous line) or oat flour (dashed line). The error bars represent the standard error in the mean, n=8.

Using a simple Elashoff equation (8) to fit the gastric chyme volume data gives emptying half time ($t_{1/2}$) values of 74 +/- 17 minutes and 84 +/- 11 minutes for the flour and flake porridge, respectively. A simple shape factor of 1 was used fit the data assuming no lag phase. This then gives mean emptying rates of 3.3 +/- 0.7 and 2.7 +/- 0.5 mL/minute respectively for the flour and flake porridge. Thus, given that the final caloric density of what was consumed in

both cases, i.e. the porridge and water was 0.54 kcal/mL, the caloric emptying rate was 1.8 and 1.5 kcal/minute for the flour and flake porridge respectively.

The data for the oat flakes suggests an initial faster rate of emptying followed by a slower rate. This is also confirmed by images of the gastric content shown in Figure 2. After 5 minutes, clear layering (phase separation) was seen in the flake porridge but the layering was no longer visible twenty minutes later indicating that the liquid layer on the top of the stomach contents had been emptied. The mean volume of this clear layer was 107 +/- 24 mL, which closely corresponds to the 115 +/- 30 mL emptied between 5 and 25 minutes after consumption of the meal. This strongly suggests that the initial emptying of the flaked porridge meal was almost entirely the liquid part and not the oat flakes themselves.

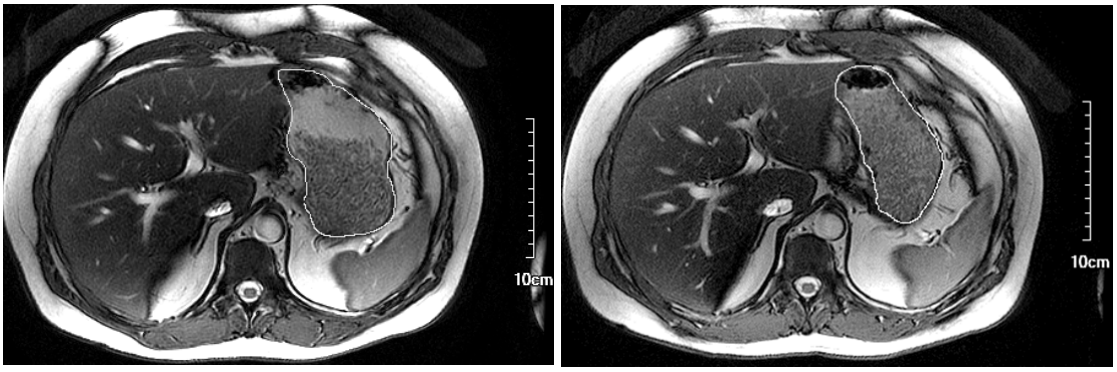

Figure 2 Axial FIESTA MRI images of the stomach (outlined) taken 5 mins (left) and 25 mins (right) post consumption. The left image shows a layer above the oat flake porridge that is not apparent after 25 mins.

In addition to measuring the volume of gastric contents, the participants were asked to complete a VAS questionnaire associated with appetite. In particular, the sensation of fullness is normally closely associated with gastric volume and also inversely associated with hunger. The data for hunger, fullness, satisfaction, desire to eat and thirst are shown in Figure 3a-e. In this case the fullness, hunger and satisfaction ratings were similar for both meals at all time points, whereas the flakes showed higher scores for desire to eat from 50 minutes after intake. The ratings for thirst showed marked differences after 90 minutes with

the flake giving more pronounced feelings of thirst. Interestingly all of the data except thirst showed a crossover at circa 100 minutes.

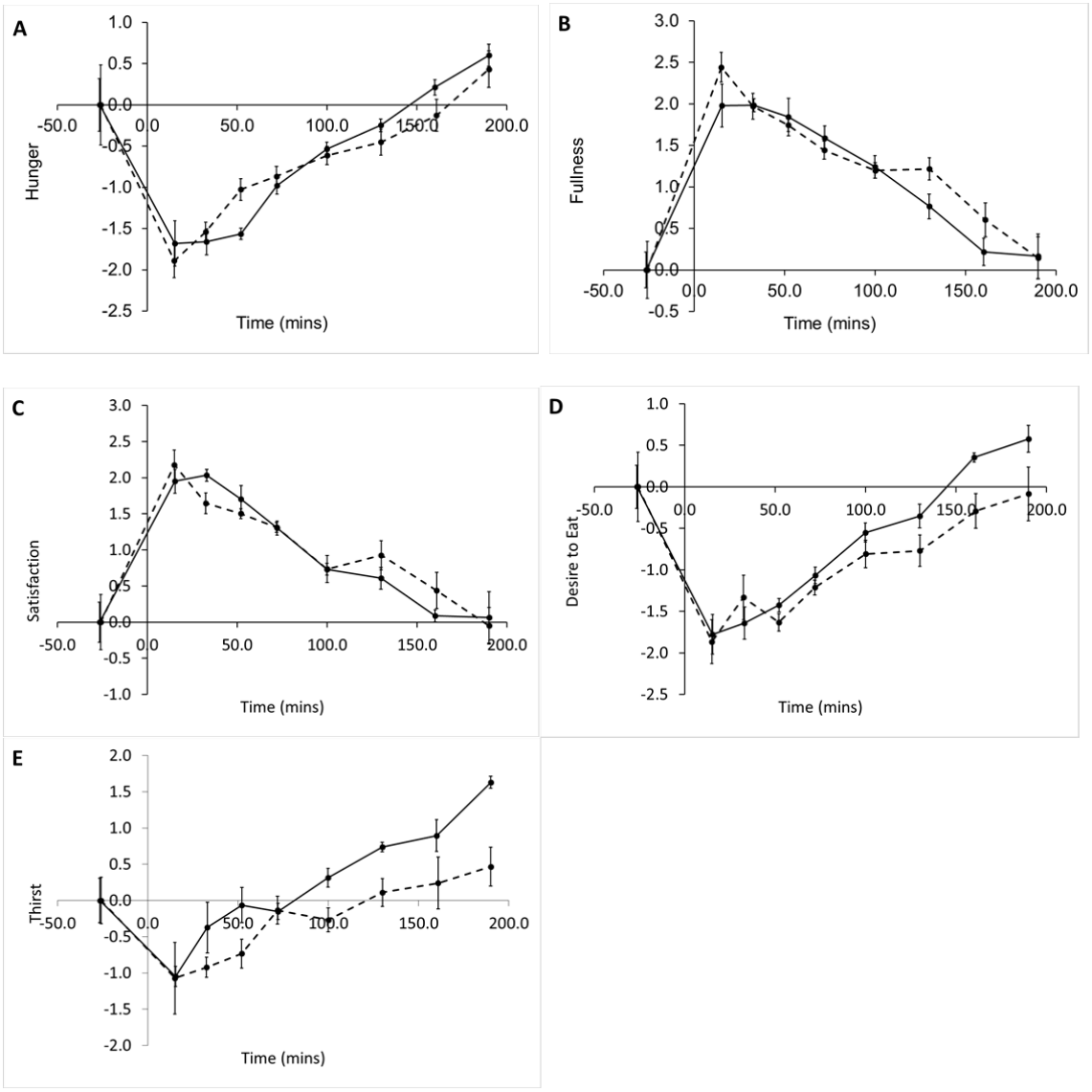

Figure 3. Normalised visual analogue scale questionnaire results shown as the mean value for hunger (A), fullness (B), satisfaction (C), desire to eat (D) and thirst (E) after consumption of either oat flakes (continuous line) or oat flour (dashed line) porridge. The error bars shown represent the standard error in the mean, n=8.

Both gastric emptying and appetite related sensations are linked to nutrient absorption and gastrointestinal hormone secretion. The results of the analysis of the blood samples taken

are shown in Figures 4 and 5. The data show that there was a small difference in peripheral glucose with the flakes giving a smaller peak at about 35 minutes post meal consumption. The incremental area under the curve (iAUC) for the glucose as calculated by the method of Brouns et al. (6) is 65.9 +/- 21.4 mM.minutes/L for the flour porridge and 46.0 +/- 37.7 mM.minutes/L for the flakes. The difference in insulin response was larger with the peak at 35 minutes markedly higher for the flour than the flakes. Although the small apparent drop of the plasma glucose below the fasted (initial) value in latter stage of the study day was within the random error of the experiment, such a drop has also been seen in similar studies (5, 16).

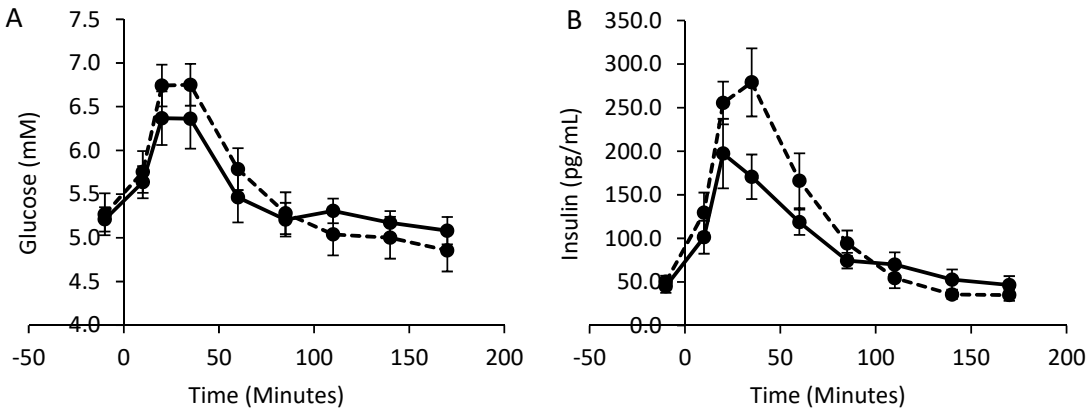

Figure 4. The average concentrations of glucose (A) and insulin (B) found in plasma after consumption of porridge made from either oat flakes (continuous line) or oat flour (dashed line). The error bars represent the standard error in the mean, n=8.

The data for the GIP and GLP-1 responses are shown in Figure 5. As both of these hormones are incretins, they both follow similar patterns. The patterns for the change in plasma concentrations of GIP and insulin are very similar after consumption of both meals, with a peak at around 30 minutes. In the case of GIP the difference between the meals is very marked, in particular at 35 minutes. The greater response was generated by the flour at all post consumption time points up to 85 minutes with the flakes giving the greater response thereafter. The GLP-1 concentration showed a difference between the two meals

at 20 minutes, with the flour giving the larger response at that time. Interestingly, the crossover in all the plasma data was at about 90-100 minutes, which is slightly after a crossover in the gastric volume curves and may indicate the time at which most of the flour porridge had been digested but when there was still glucose from the flake porridge being absorbed.

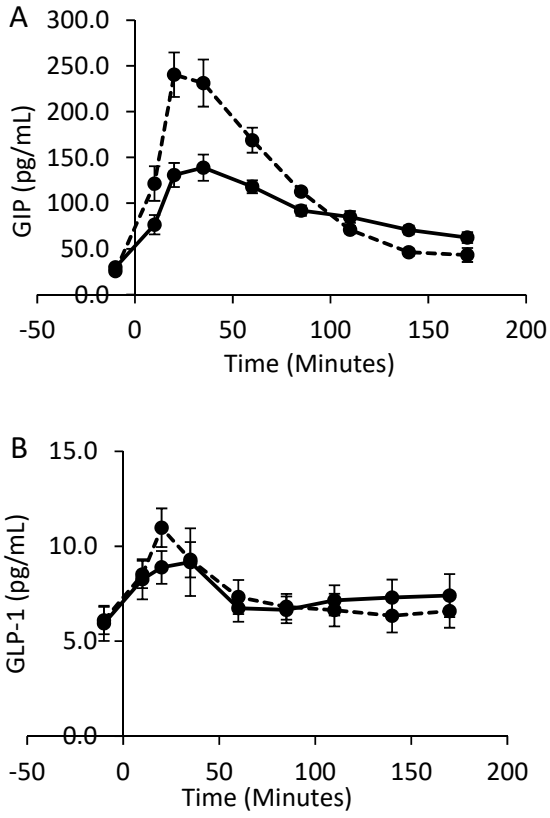

Figure 5. The average concentrations of GIP (A) and GLP-1 (B) found in plasma after consumption of porridge made from either oat flakes (continuous line) or oat flour (dashed line). The error bars represent the standard error in the mean, n=8.

In order to investigate the role of β-glucan in the late period of digestion, when the crossover was observed in blood parameters and VAS measures, simulated intestinal viscosity and β-glucan release were obtained after *in vitro* digestion. The two porridge samples did not differ in β-glucan Mw with values of 1097 +/- 14 and 1107 +/- 17 for the flour and flakes respectively. However, more β-glucan was solubilized in the flour porridge (37.5 +/-1.8%)

311 compared to the flake porridge (28.5 +/- 1.5%) and the viscosity of the extract was also
312 slightly higher for the flour porridge (1.38 +/- 0.02 mPas) compared to the flake porridge
313 (1.17 +/- 0.01 mPas).

314 An overview and validation of the effects produced by the digestion of the two porridge
315 meals is provided by PLS-DA discriminant analysis performed at an early time point, i.e. 35
316 min after consumption of the porridge (Figure 6 a and b), and a later time point, i.e. 180 min
317 after consumption (Figure 6 c and d).

318 In the score plots of the samples, displayed in Figure 6a (35 min) and Figure 6c (180 min),
319 the flour is located towards the upper right corner and the flakes are located towards the
320 lower left corner. The loading plot at 35 min (Figure 6b) reflects the higher levels of glucose,
321 insulin, and GIP, as well as higher ratings of hunger observed for the flour porridge at this
322 time point. All these features are located towards the right hand side in the loading plot, and
323 so is the response variable “flour”. At the later time point (180 min) (Fig 6 c and d) this
324 pattern is changed, with the flake porridge associated with the highest ratings of hunger and
325 desire to eat, and the flour porridge with higher fullness and satisfaction. The plasma levels
326 of glucose, insulin and GIP, as well as the gastric volume, were highest for the flake porridge
327 at this time point.

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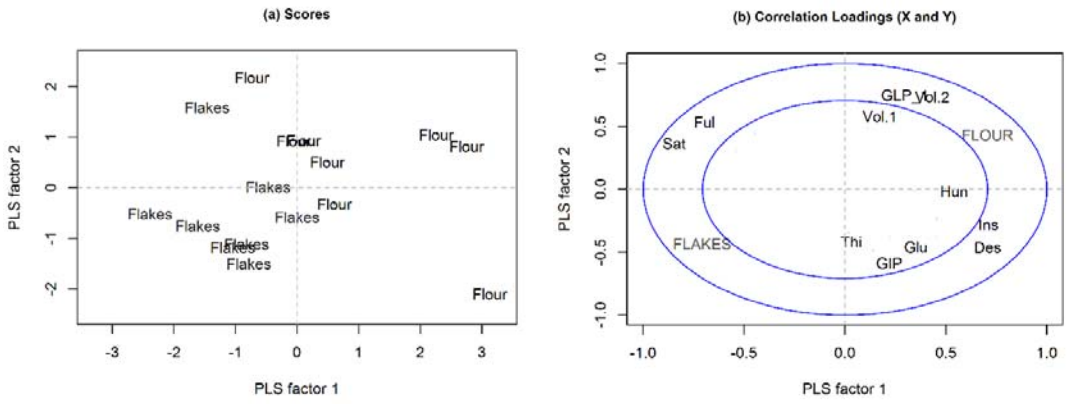

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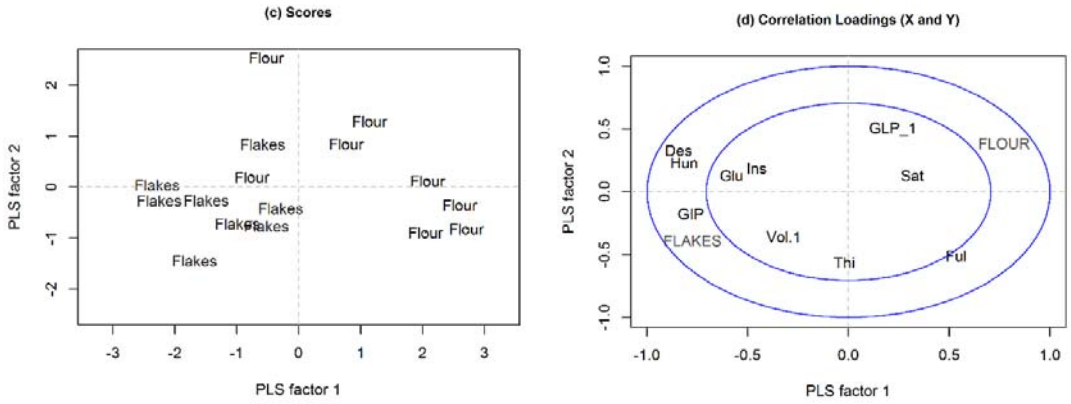

330 *Figure 6. Multivariate data analysis (PLS-DA) of the observed data on glucose, insulin, GIP,*
331 *gastric volume and satiety sensations, with porridge type (flakes and flour) as two response*
332 *classes. Fig. 6a and b show the results 35 min after intake of porridge, and Fig. 6c and d*
333 *show the results 180 min after intake. Fig. 6a and c are score plots of the samples, and Fig.*
334 *6b and d show the corresponding loadings of the input variables and the responses, n=8.*

335

336 **Discussion**

337 Once consumed, food passes into the stomach, where it stays until it is emptied into the
338 duodenum. In the time that it resides in the stomach a number of changes can take place
339 including digestion by gastric and oral enzymes depending on local pH and phase
340 separation (25). In this case the oat flake porridge showed significant signs of sedimentation
341 of the flakes immediately post consumption (figure 2a). The absence of the liquid phase

above the flakes in the image taken 20 minutes later shows that the flakes remained sufficiently intact to be prevented from passing through the pylorus into the duodenum. This confirms that a good proportion of the original flake porridge meal remained in the stomach longer than flour porridge meal. However, does this mean that the starch in that porridge remained associated with the flakes and thus was not emptied into the duodenum? The lower peak in plasma glucose, insulin and GIP certainly suggest that this was the case.

The most significant difference in the plasma components that were measured was seen in glucose-dependant insulinotropic peptide (GIP). The secretion of GIP by K-cells is driven by the rate of nutrient absorption in the proximal small intestine, especially glucose or fat (1). The primary role of GIP is in the pancreas where it binds to its specific receptor (GIPR) on β-cells and enhances glucose dependent insulin secretion. Thus, it is no surprise that the GIP response is mirrored by the insulin response to both meals but to a lesser extent. In a recent study, Trahair et al. sought to determine the effect of two different rates of intraduodenal glucose infusions (1 or 3 kcal/min) on glycemic, insulinemic and incretin hormone responses in lean and obese subjects, and compare the effects of oral and intraduodenal glucose in obese subjects (37). This was done to mimic different rates of gastric emptying. Unsurprisingly, the faster delivery of glucose in their study gave higher responses in glucose, insulin and GIP. In the healthy control group, the pattern was very similar to that seen in this study with the GIP response the largest followed by the insulin and then the plasma glucose. This was not the case in the obese group, where the GIP response was less significant than either the insulin or glucose responses. The authors concluded that the rate of duodenal delivery of glucose is a major determinant of glycaemia in obese subjects and that "strategies that slow gastric emptying may prevent progression to type 2 diabetes in obesity warrants exploration." In the work presented here we have started that exploration.

The particle size (flour vs flakes) in oat porridge significantly influenced the glycemic response. The peaks in blood glucose, insulin and GIP observed 30-40 min after intake were significantly higher for the flour porridge compared to the flake porridge. The MRI analyses

indicate that this was not due to a more rapid gastric emptying after intake of flour porridge. However the composition of what was emptied from the stomach could have been very different because of the gastric sieving effect. The higher glycemic response is therefore more likely reflecting increased starch hydrolysis in the intestine due to more easily available starch in the flour than the flakes.

In an attempt to unify all of the data including the subjective appetite scores, a multivariate analysis was undertaken. Results from the PLS-DA also reflect the differences in glycemic response. Over the time course, the plasma levels of glucose, insulin and GIP declined for both porridges, resulting in a shift after approximately 2 hours when the flour porridge showed slightly lower levels of glucose, insulin and GIP than the flake porridge. Similarly, the satiety data changed with time. At 35 min after ingestion the flake porridge was associated with lower hunger, whereas at 180 min the flake porridge got the highest ratings of hunger and desire to eat. Although the satiety data correlated well with the levels of plasma glucose, insulin and GIP at both time points (low levels were associated with higher fullness and satisfaction), there may not be any cause and effect relationship. It is unlikely that the glycemic or insulin response can explain the shift in satiety taking place from 35 to 180 min after ingestion. Neither were there any strong correlations between satiety ratings and gastric volume. Hence, there must be other explanations for the differences in satiety.

At the early time point (35 min) the flake porridge was considered as more satiating than the flour porridge. MRI analysis indicated that the liquid layer on the top of the stomach content is rapidly emptied during this period. The flake porridge also gave a more pronounced feeling of thirst, which may indicate that the flake porridge was more viscous in the stomach than the flour porridge (26, 27). Viscosity has been shown to have an effect on satiety and fullness in many studies, but may not affect fullness through delayed gastric emptying (10, 18). Hence, the increased perceived fullness observed after ingestion of flake porridge in the present study may be due to increased viscosity in the stomach, not generated by the starch

and β-glucan but rather the persistent structure of the flakes. At later time points, the flour porridge was associated with higher fullness and satisfaction. This may be due to the higher release of β-glucan from the flour porridge (37.5 %) compared to the flake porridge (28.5 %) as measured after *in vitro* digestion. Hence, the smaller particle size in flour compared with flakes makes the β-glucan more available and resulted in a higher viscosity in the intestinal phase for the porridge made from flour compared with the porridge made with flakes. Increased viscosity may have an effect on nutrient digestion and uptake, and, hence, the stimulation of release of satiety hormones. However, it should be noted that the viscosity difference between the two porridge samples ($p = 0.053$) was very small (0.21mPas). It is therefore unlikely that the viscosity difference alone can explain the different outcomes for the two porridges at later time points of digestion and other mechanisms may be involved. It is possible that the higher amount of solubilized β-glucan in the flour porridge still plays a role, for example by decreasing the permeability of the intestinal mucus layer (19). Previous studies have shown that increasing amounts of β-glucan lower postprandial blood glucose and insulin levels (21). In the present study, a potential inhibiting effect of β-glucan on the uptake of glucose seemed minor compared to the effect of more available starch in the duodenum.

In summary, the results suggest that there are two main phenomenon taking place. Firstly, decreased gastric emptying of flakes in comparison to the increased availability of starch in the flour porridge resulted in a more pronounced glycemic response from the flour. Secondly, increased availability of β-glucan caused increased perceived satiety in the flour after 2 hours. Neither satiety nor glycemic response appeared to be related to gastric emptying rate.

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Disclosures

No financial conflicts, financial or otherwise are declared by the authors

Author Contributions

A.R.M., L.J.S., B.H.B. and N.M.R. performed the experiments; A.R.M., BHB and EFM analyzed data; A.R.M., B.K., and E.F.M. interpreted results of experiments; A.R.M. and E.F.M. prepared figures; A.R.M. drafted the manuscript; A.R.M., P.J.W., E.F.M. and B.K. edited and revised manuscript; A.R.M., PJ.W., P.M. and B.K. approved final version of manuscript.

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Figure Captions

Figure 1: Total volume of gastric content (excluding gas) after consumption of porridge made from either oat flakes (continuous line) or oat flour (dashed line). The error bars represent the standard error in the mean, n=8.

Figure 2. Axial FIESTA MRI images of the stomach (outlined) taken 5 mins (left) and 25 mins (right) post consumption. The left image shows a layer above the oat flake porridge that is not apparent after 25 mins.

Figure 3. Normalized visual analogue scale questionnaire results shown as the mean value for hunger (A), fullness (B), satisfaction (C), desire to eat (D) and thirst (E) after consumption of either oat flakes (continuous line) or oat flour (dashed line) porridge. The error bars shown represent the standard error in the mean, n=8.

Figure 4. The average concentrations of glucose (A) and insulin (B) found in plasma after consumption of porridge made from either oat flakes (continuous line) or oat flour (dashed line). The error bars represent the standard error in the mean, n=8.

Figure 5. The average concentrations of GIP (A) and GLP-1 (B) found in plasma after consumption of porridge made from either oat flakes (continuous line) or oat flour (dashed line). The error bars represent the standard error in the mean, n=8.

Figure 6. Multivariate data analysis (PLS-DA) of the observed data on glucose, insulin, GIP, gastric volume and satiety sensations, with porridge type (flakes and flour) as two response

578 classes. Fig. 6a and b show the results 35 min after intake of porridge, and Fig. 6c and d
579 show the results 180 min after intake. Fig. 6a and c are score plots of the samples, and Fig.
580 6b and d show the corresponding loadings of the input variables and the responses, n=8.

581 Table 1 Composition and nutritional information of the two porridge meals

Ingredient	**Oat flakes**		**Oat flour**	
Flakes/ flour (g)	35.2		35.2	
Skimmed milk (g)	110		110	
Water (g)	110		110	
Margarine (g)	6.6		6.6	
Sugar (g)	1.98		1.98	
Salt (g)	0.11		0.11	
Total amount (g)	*264*		*264*	
Kcal for 264 g portion	237.6		237.6	
Nutrition	**g / 100g**	**g / 264g**	**g / 100g**	**g / 264g**
Fat	2.94	7.76	2.94	7.76
Carbohydrate	11.7	30.9	11.7	30.9
Fiber	1.66	4.38	1.66	4.38
Beta-glucan	0.54	1.43	0.54	1.43
Protein	3.36	8.87	3.36	8.87
*Salt	0.80	2.11	0.80	2.11

582

583 Table 2. Participant clinical characteristics

Participant ID	Age (years)	Height (cm)	Weight (kg)	BMI (Kg/m^2)	Blood pressure (mmHg)	Resting heart rate (BPM)
OM01	48	176.6	81.2	26	138/82	57
OM02	48	179.6	89.1	27.6	120/84	61
OM03	53	188.9	94.9	26.6	124/79	53
OM04	48	178.8	75.7	23.7	129/84	70
OM06	38	178.7	94.5	29.6	129/78	63
OM07	46	173.6	78.7	26.1	137/82	60
OM08	53	188.9	92.3	25.9	123/73	56
OM09	37	193.8	96.4	25.7	137/88	61

584

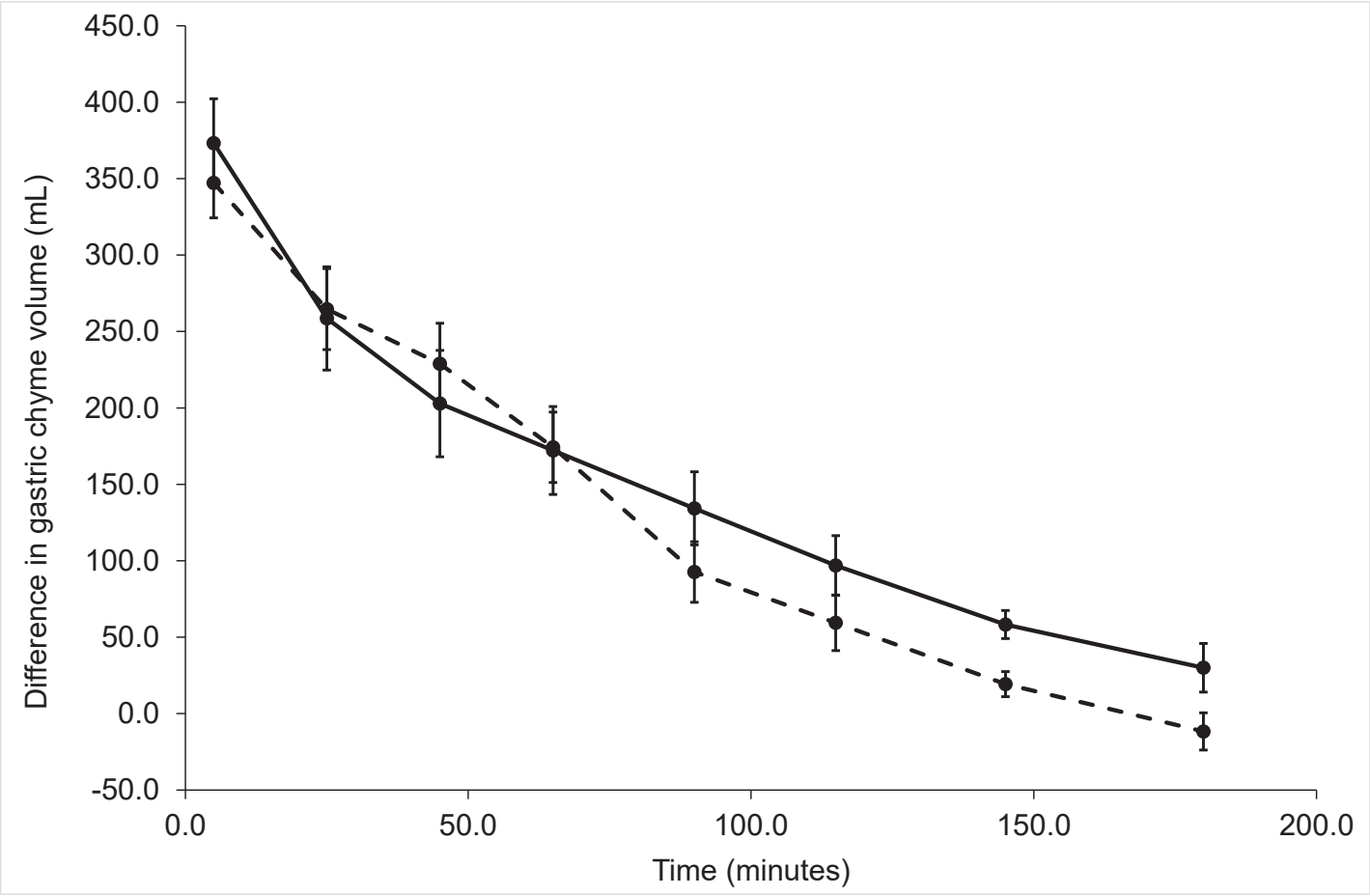
585 Table 3 Timing of the study protocol. All times are given in minutes after completion of meal
586 consumption with the exception of the first row, which indicates the time prior to meal
587 consumption of the porridge.

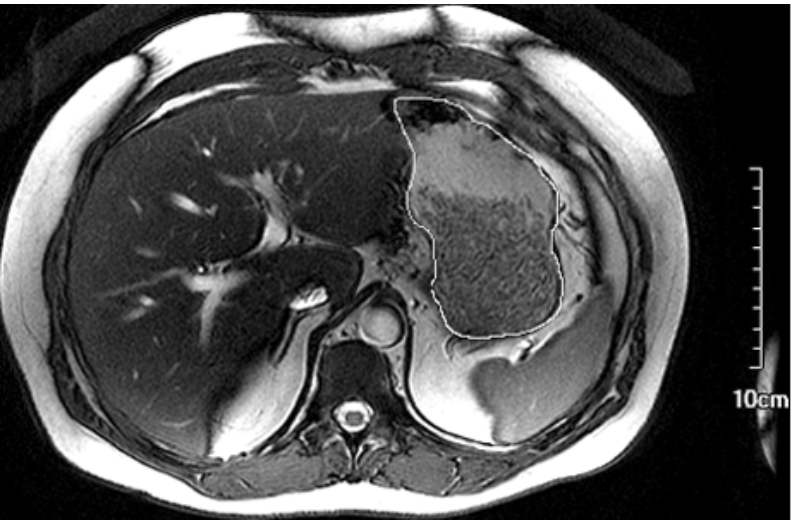
Time point	MRI scan	Blood sampling	VAS questionnaire
1	-15	-10	-5
2	5	10	15
3	25	20	30
4	45	35	50
5	65	60	70
6	90	85	100
7	115	110	130
8	145	140	160
9	180	170	190

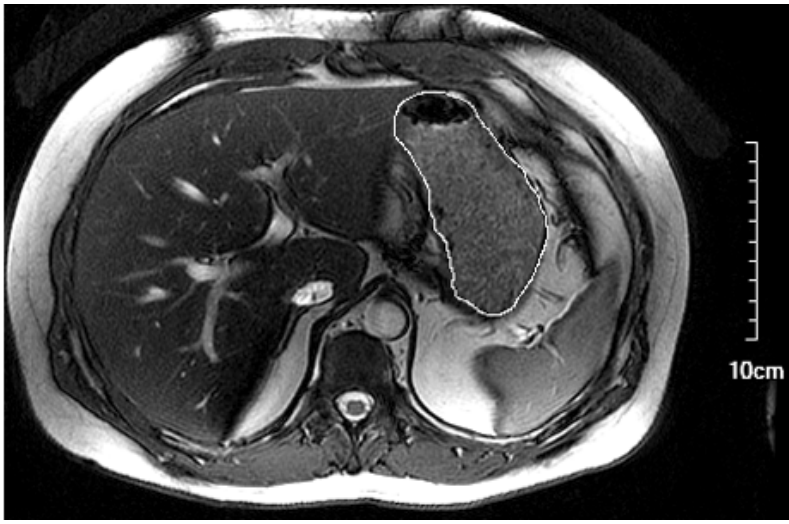
588

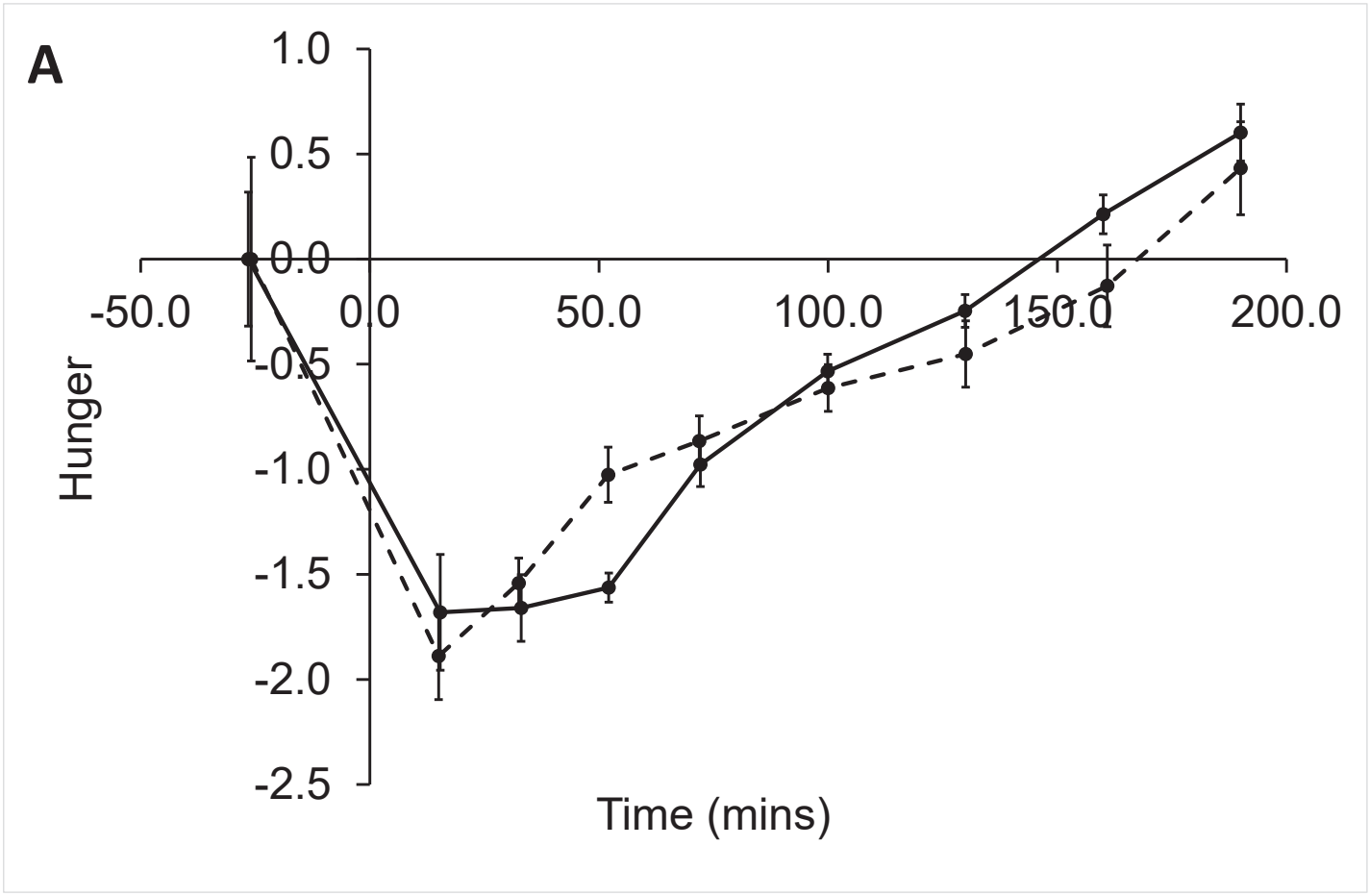
589

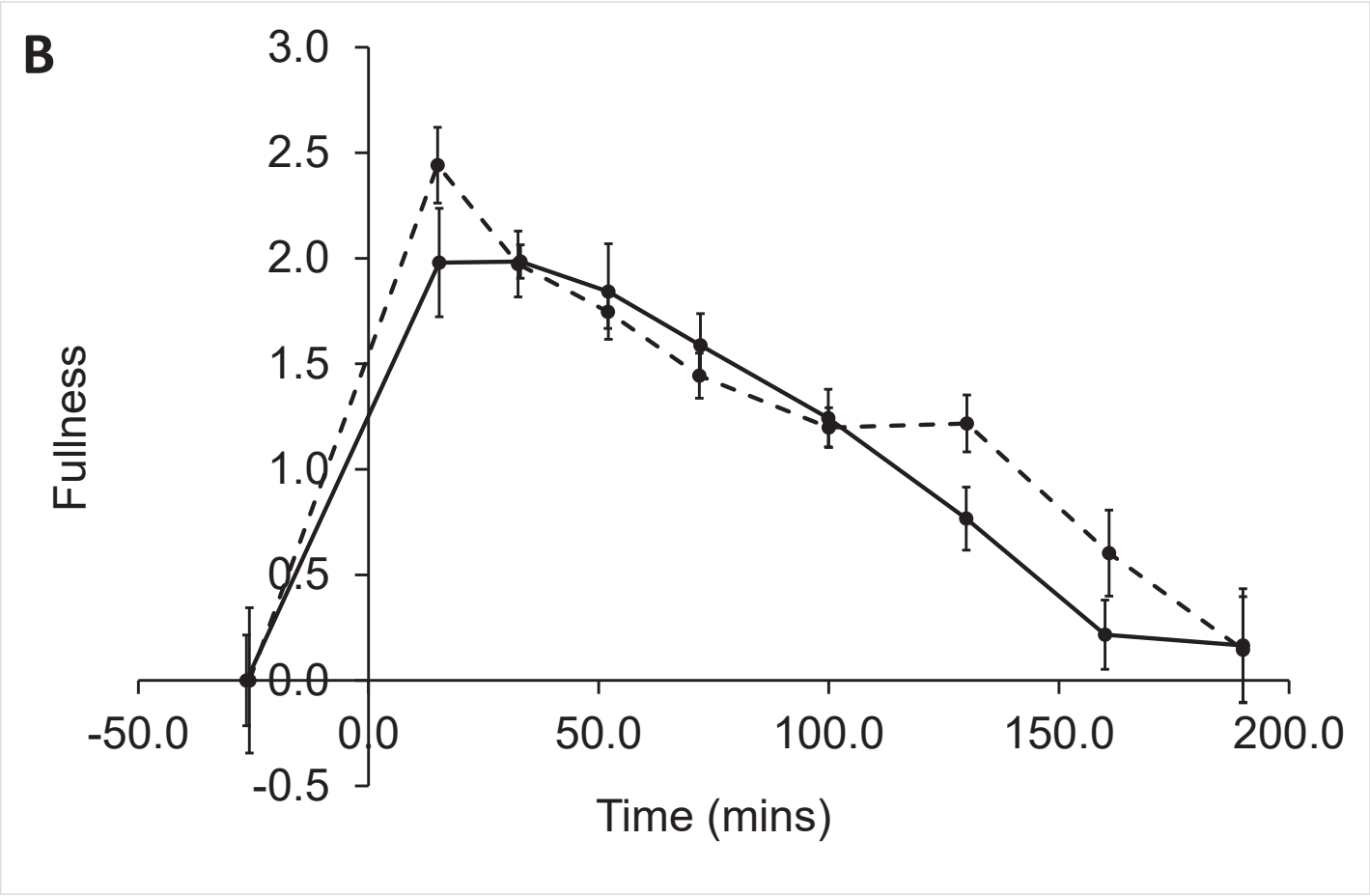
590

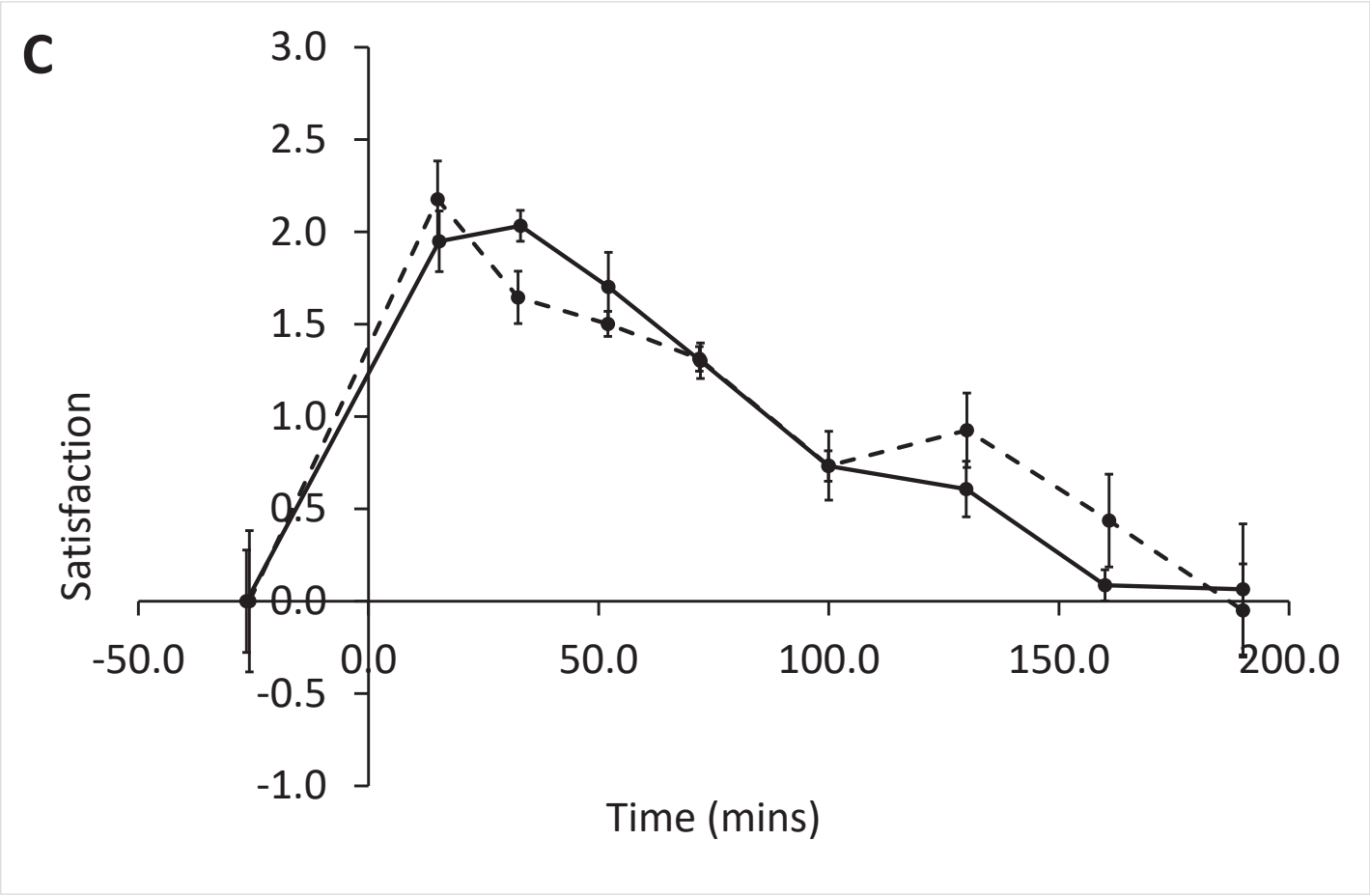

450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
-50.0
Difference in gastric chyme volume (mL)
0.0
50.0
100.0
150.0
200.0
Time (minutes)

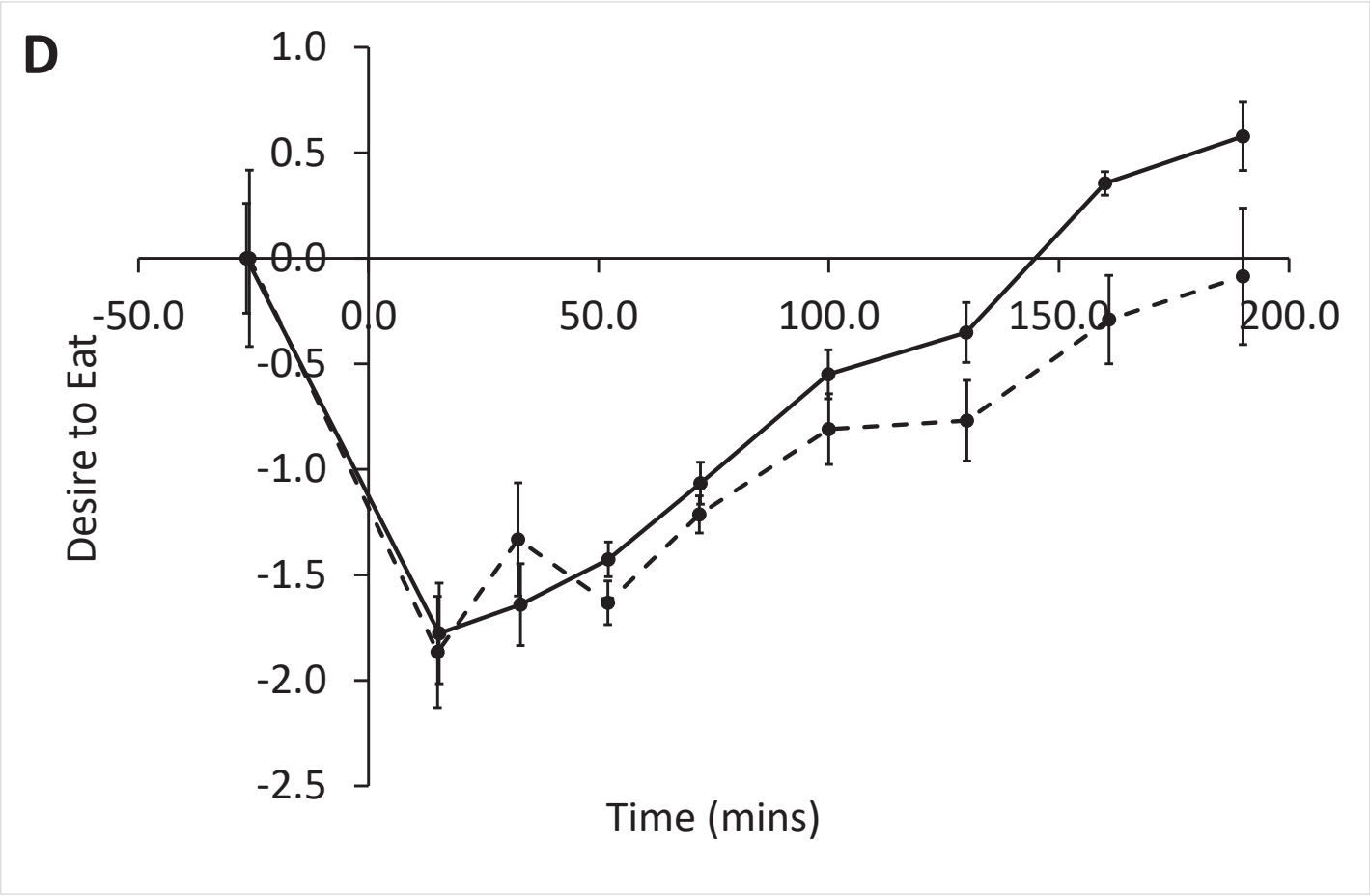

10cm

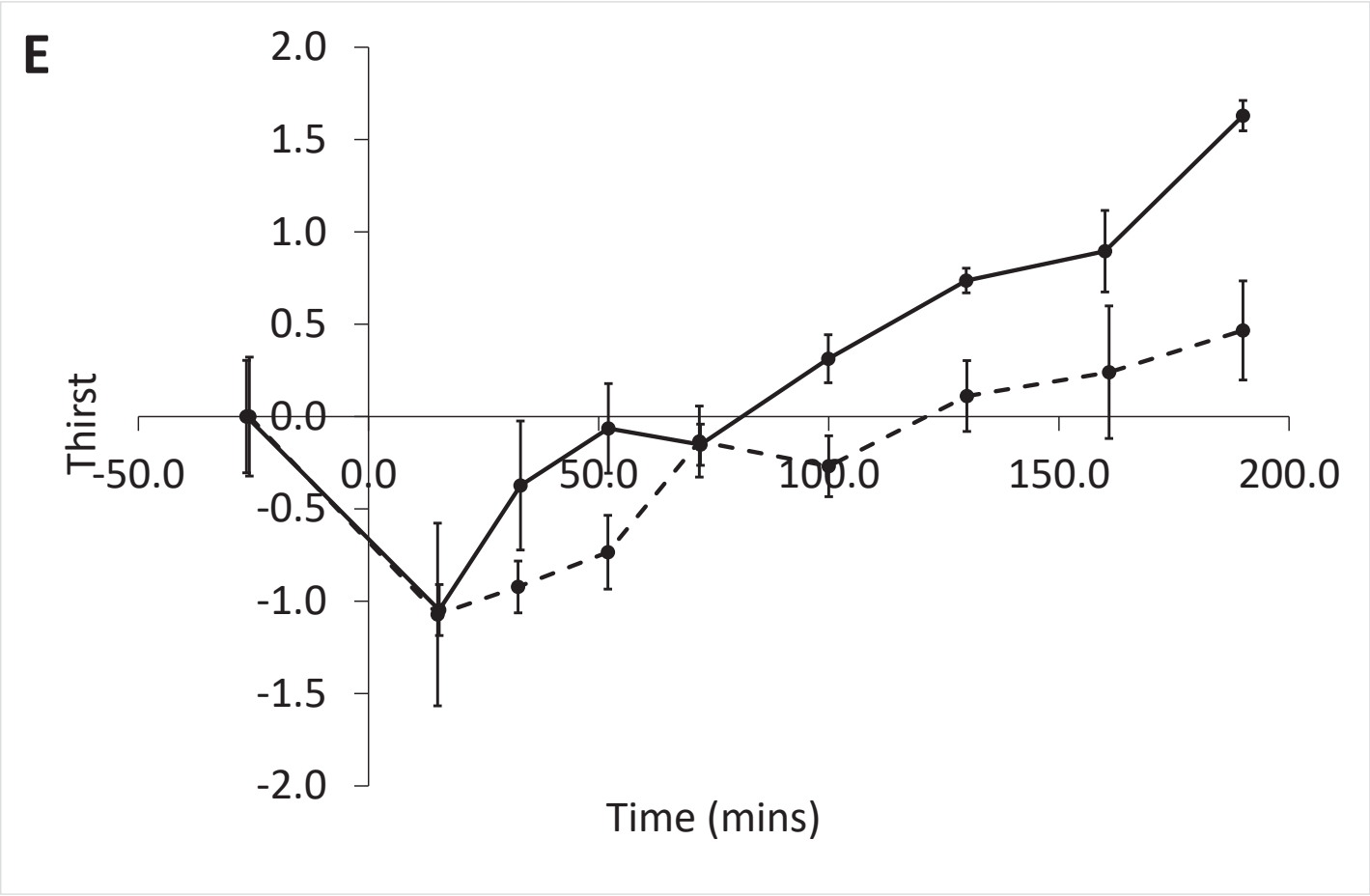

10cm

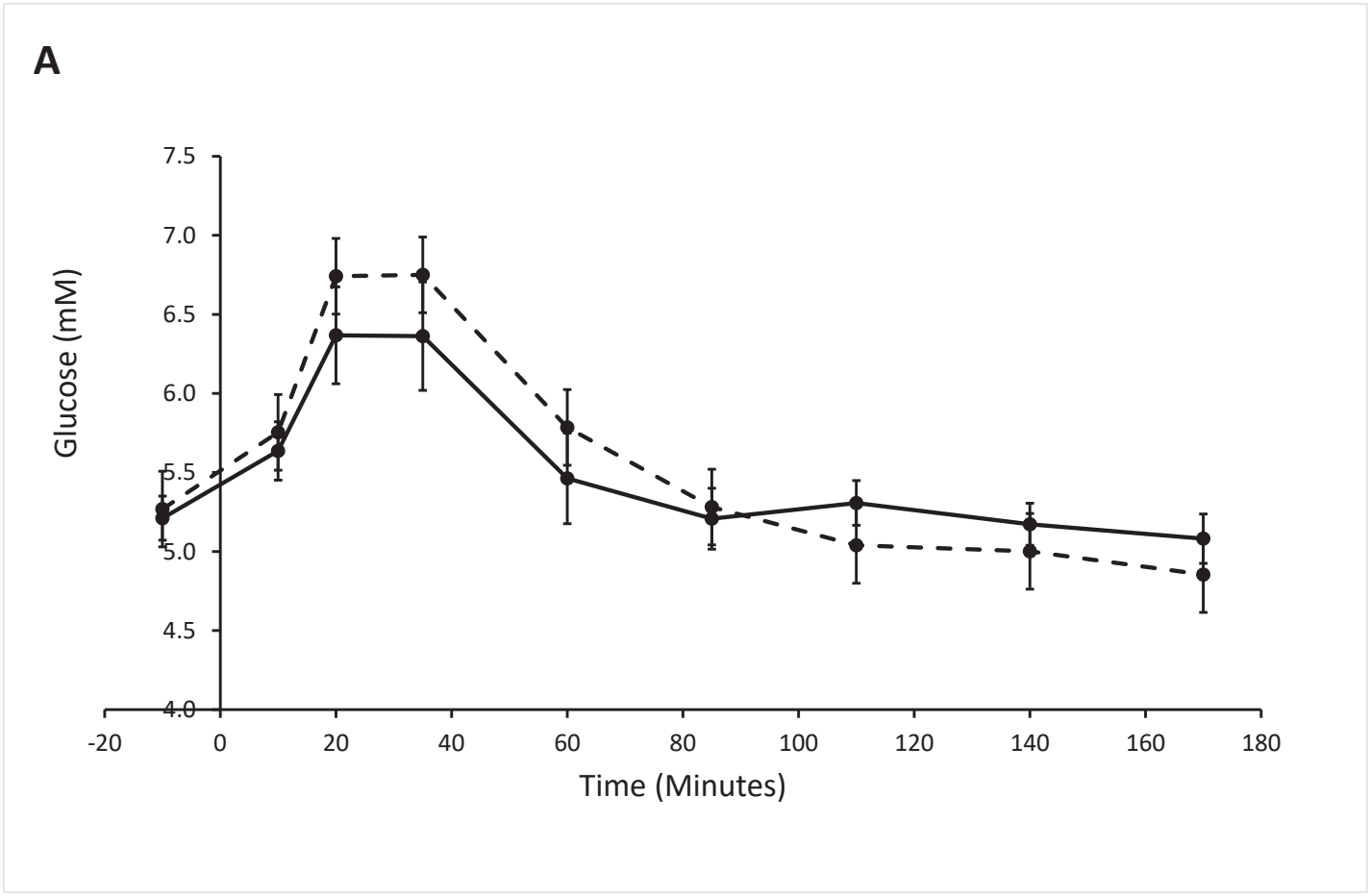

A
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-50.0
0.0
50.0
100.0
150.0
200.0
Hunger
Time (mins)


B
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
Fullness
-50.0
0.0
50.0
100.0
150.0
200.0
Time (mins)

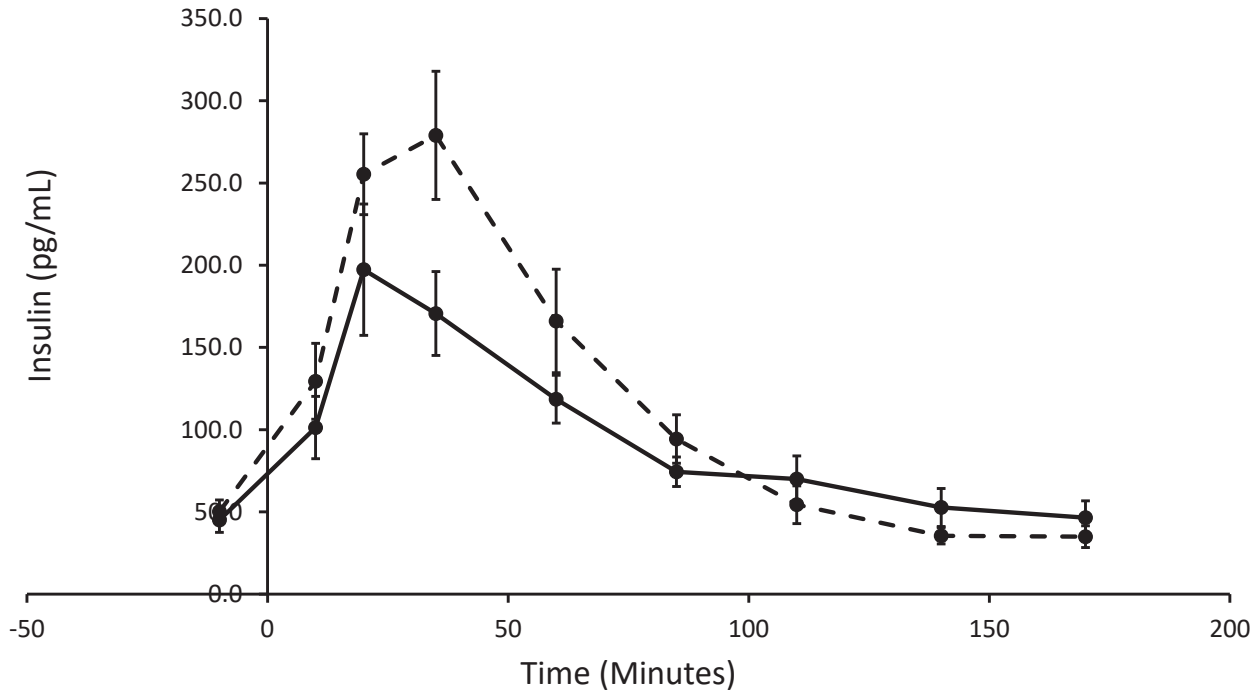

C
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
Satisfaction
-50.0
0.0
50.0
100.0
150.0
200.0
Time (mins)

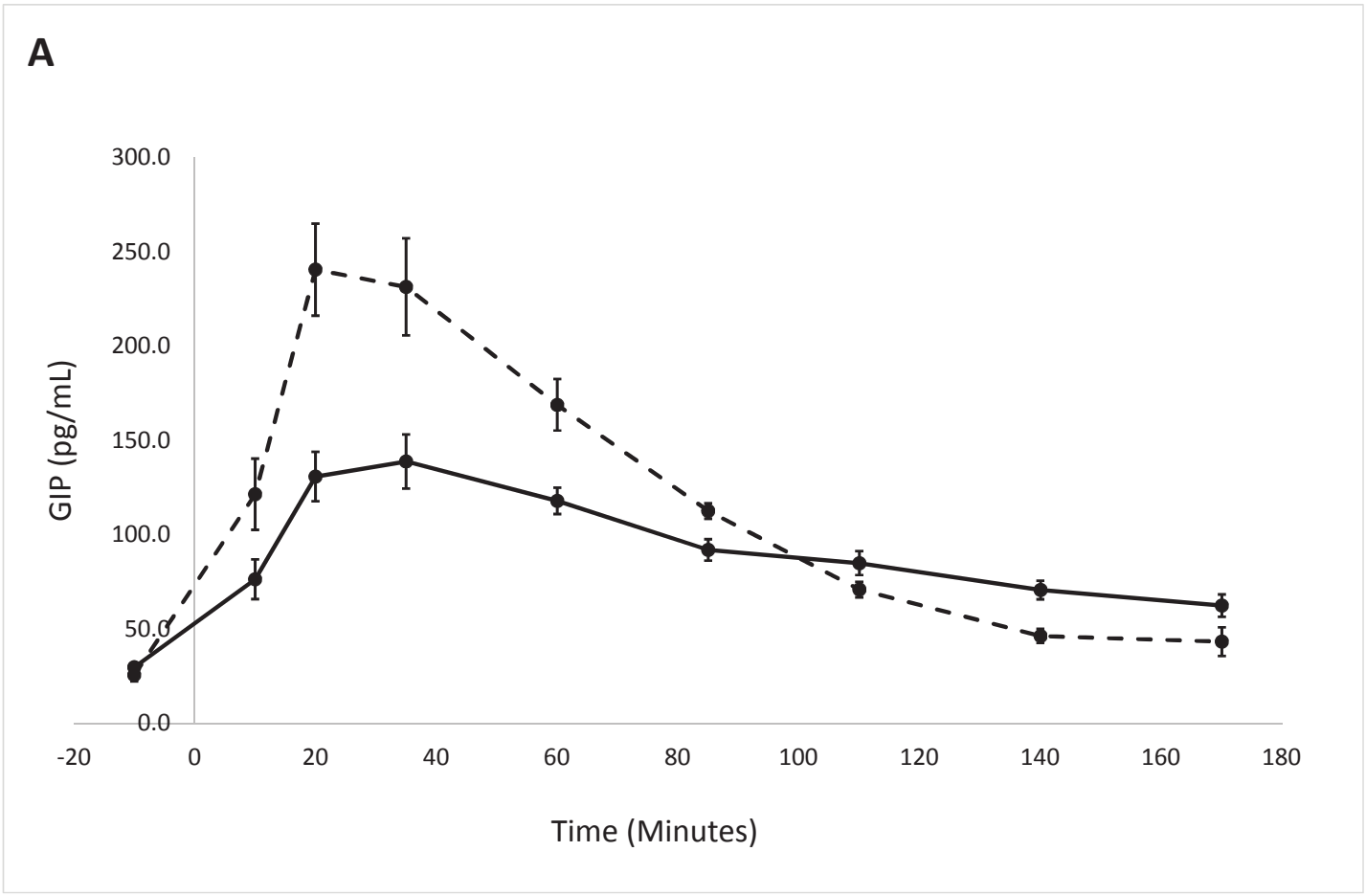

D
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-50.0
0.0
50.0
100.0
150.0
200.0
Desire to Eat
Time (mins)


E
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Thirst
-50.0
0.0
50.0
100.0
150.0
200.0
Time (mins)

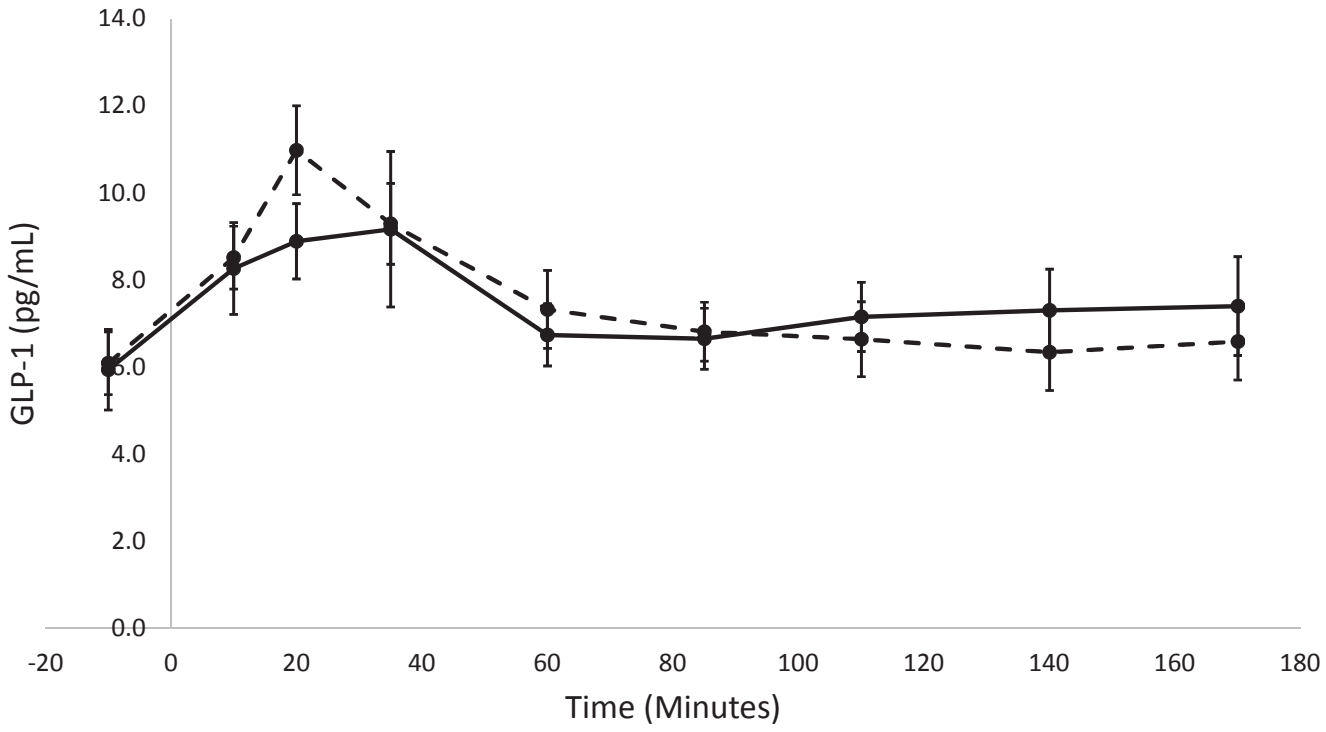

A
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
Glucose (mM)
-20
0
20
40
60
80
100
120
140
160
180
Time (Minutes)

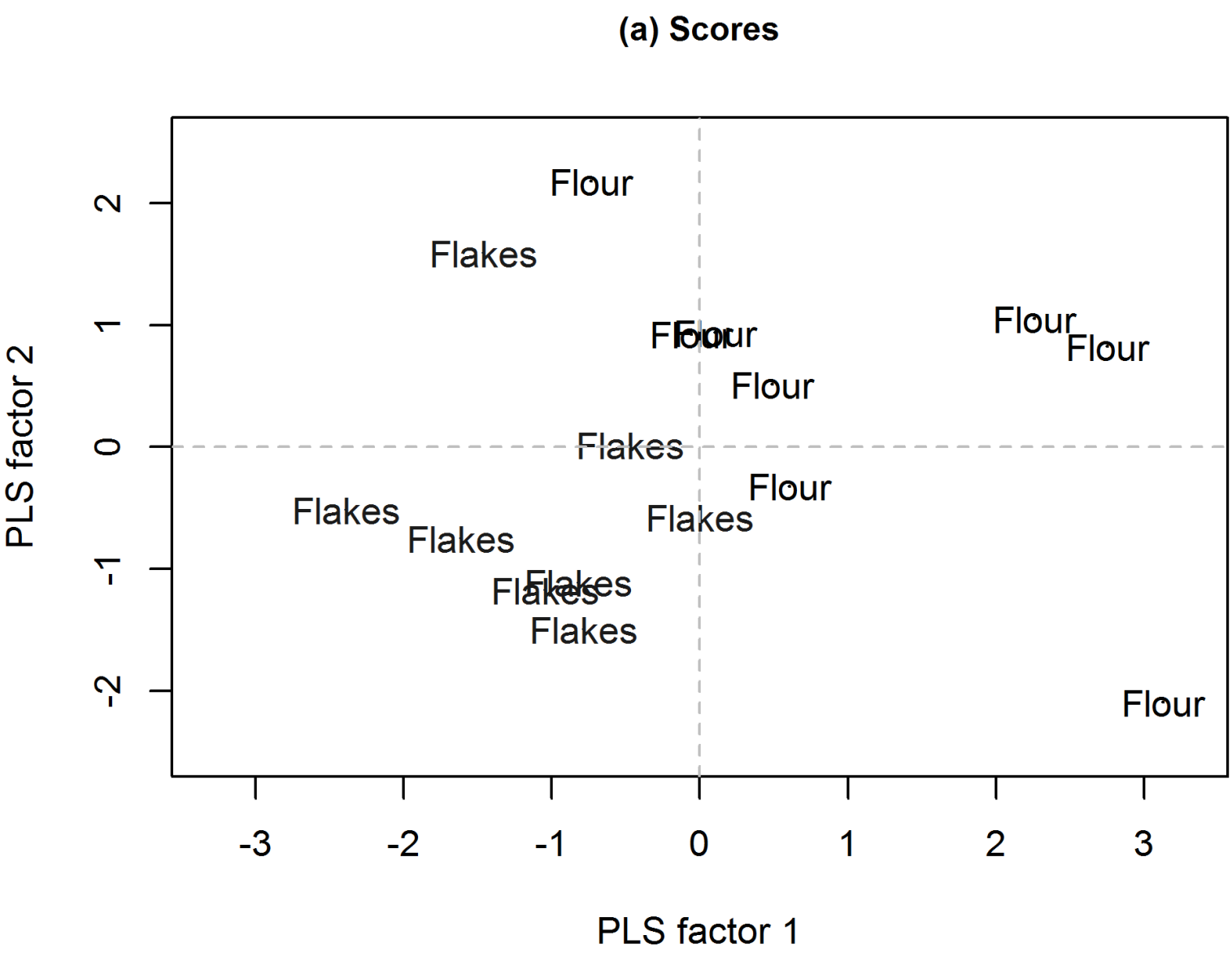
B

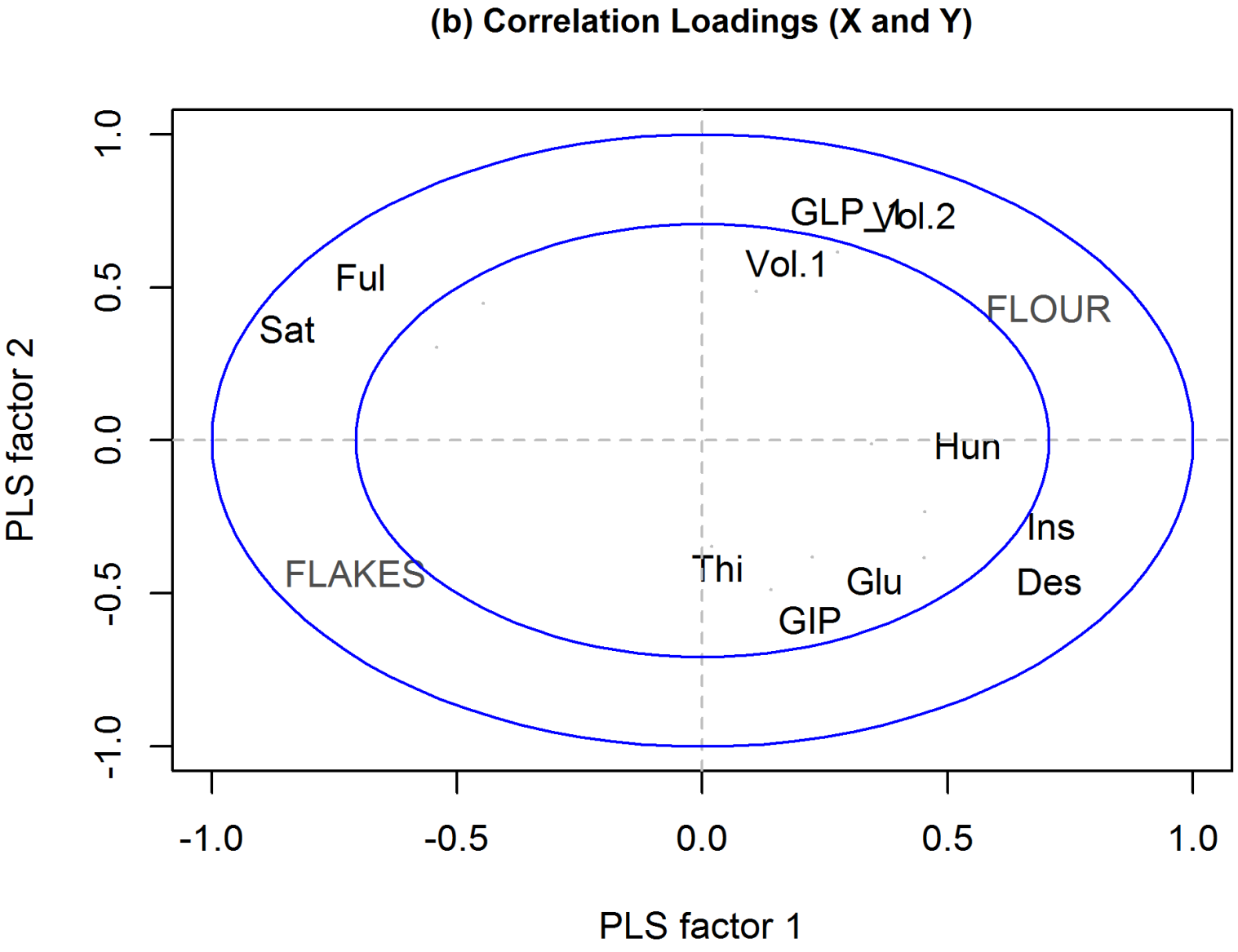

350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Insulin (pg/mL)
-50
0
50
100
150
200
Time (Minutes)

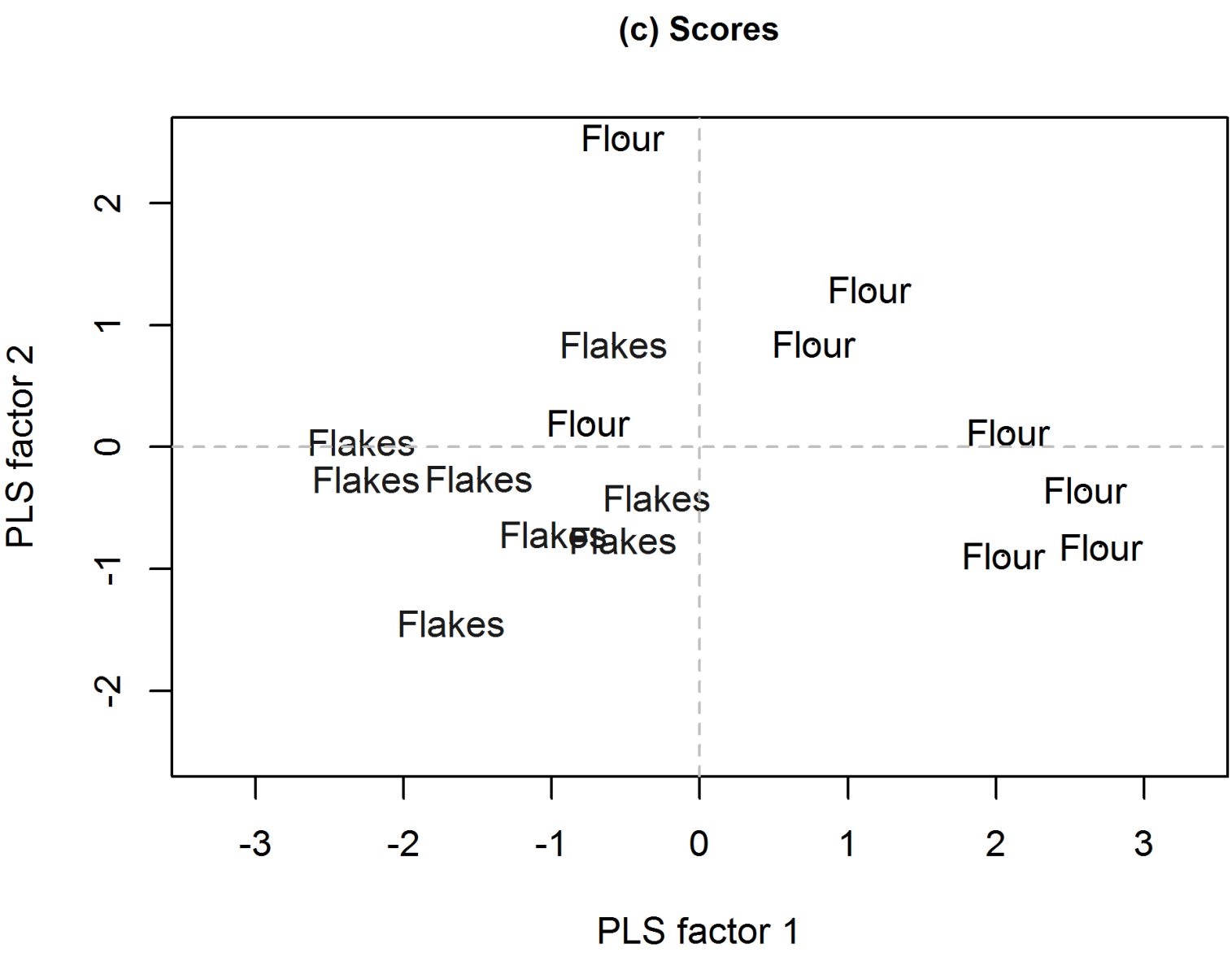

A
300.0
250.0
200.0
150.0
100.0
50.0
0.0
GIP (pg/mL)
-20
0
20
40
60
80
100
120
140
160
180
Time (Minutes)

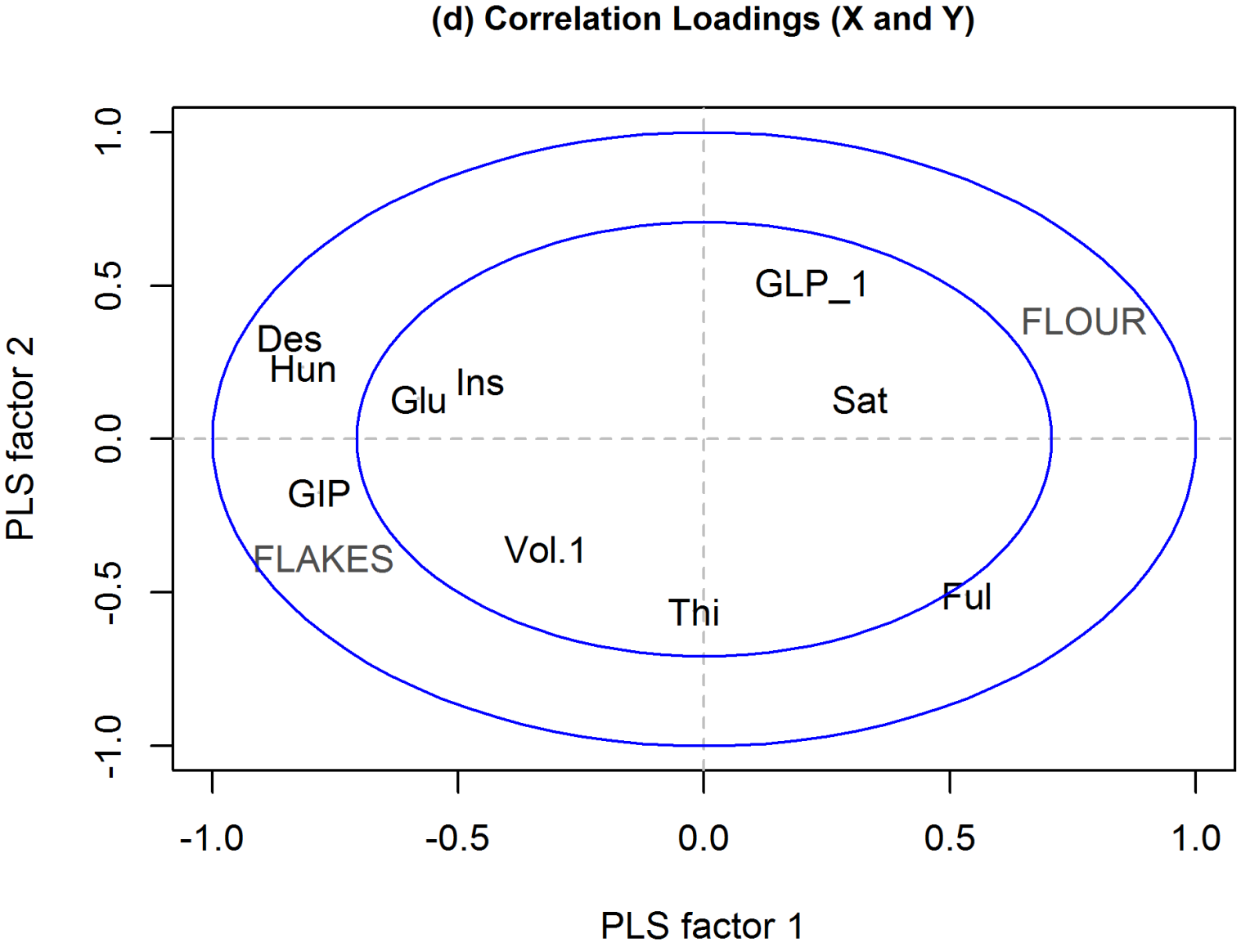
B


14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
GLP-1 (pg/mL)
-20
0
20
40
60
80
100
120
140
160
180
Time (Minutes)


(a) Scores
Flour
Flakes
Flour
Flour
Flour
Flour
Flour
Flakes
Flour
Flakes
Flakes
Flakes
Flakes
Flakes
Flakes
Flour
PLS factor 2
2
1
0
-1
-2
-3
-2
-1
0
1
2
3
PLS factor 1


(b) Correlation Loadings (X and Y)
PLS factor 2
PLS factor 1
1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0
GLP_1
Vol.2
Vol.1
Ful
Sat
FLOUR
Hun
Ins
Des
Glu
GIP
Thi
FLAKES


(c) Scores
Flour
Flour
Flour
Flakes
Flour
Flour
Flakes
Flakes
Flakes
Flakes
Flakes
Flakes
Flakes
Flour
Flour
Flour
Flour
PLS factor 2
2
1
0
-1
-2
-3
-2
-1
0
1
2
3
PLS factor 1


(d) Correlation Loadings (X and Y)
PLS factor 2
PLS factor 1
1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0
GLP_1
FLOUR
Des
Hun
Glu
Ins
Sat
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Thi
Ful