The impact of nutrition on social decision making

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Abstract

Food intake is essential for maintaining homeostasis, which is necessary for survival in all species. However, food intake also impacts multiple biochemical processes that influence our behavior. Here, we investigate the causal relationship between macronutrient composition, its bodily biochemical impact and a modulation of human social decision making. Across two studies, we showed that breakfasts with different macronutrient compositions modulated human social behavior. Breakfasts with a high carbohydrate/protein ratio increased social punishment behavior in response to norm violations compared to that in response to a low carbohydrate/protein meal. We showed that these macronutrient-induced behavioral changes in social decision making are causally related to a lowering of plasma tyrosine levels. The findings indicate that, in a limited sense, 'we are what we eat' and provide a novel perspective on a nutrition-driven modulation of cognition. The findings have implications for education, economics and public policy and emphasize that the importance of a balanced diet may extend beyond the mere physical benefits of adequate nutrition.

Significance statement

Food intake is essential for survival in all species for meeting energetic demands. However, food intake also modulates various biochemical processes underlying cognition. Across two studies, we showed that different macronutrient compositions in standard European meals affect plasma neurotransmitter precursor levels, and these in turn influence social decision making. Our results provide evidence that variations in the macronutrient content of a normal European meal exert a significant impact on high level human cognition. This study opens novel perspectives on nutrition-driven cognition modulation. The results have implications for education, economics and public policy by emphasizing the importance of a balanced diet on fundamental expressions of cognition.

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Food intake is a fundamental basis for survival in all living organisms insofar as an adequate daily food intake secures energy levels (1). Each meal contains a different macronutrient composition that in turn influences a variety of biochemical processes (2, 3). In addition to supplying the body with nutrients, these biochemical processes also influence brain processes, including higher level cognition such as social decision making (4, 5). Therefore, it is not only whether and when we eat that is important, but equally what we eat.

Macronutrient composition, the relation of fat, protein and carbohydrates, is known to modify endocrine signals (6–8). More specifically, large neutral amino acids (LNAAs; 9) can act to modulate brain neurotransmitter dynamics (10). Specifically, consuming protein-rich food has been shown to alter blood tyrosine levels (a LNAA and precursor of dopamine; 2), whereas the intake of carbohydrate-rich food increases blood tryptophan levels (a LNAA and precursor of serotonin; 2). Furthermore, this change in peripheral LNAA levels has been linked to brain dopamine and serotonin synthesis (SI; 11–13).

On the other hand, social decisions such as helping, trusting or social punishment (usually assessed as rejection rates in the ultimatum game, UG) are susceptible to influences from hormonal and neurotransmitter states (3, 5, 14). Human studies on neuromodulation typically induce supra-physiological effects, for example, through pharmacological manipulations that are beyond that induced by regular food intake (e.g., 2 vs. 4). Other studies have attempted to manipulate blood glucose concentrations either by drinks containing glucose or through cognitive exercises thought to deplete glucose resources (3, 15). In contrast to highly selective pharmacological interventions or the impact of glucose-containing drinks, a balanced meal contains a mixture of proteins and carbohydrates, leading to physiological fluctuations evident across a range of metabolic parameters. However, it is unknown whether the macronutrient composition of a simple western-style meal is sufficient to change metabolic parameters that in turn impacts social decision making.

In this study, we investigated the impact of the macronutrient composition of a typical western-style meal on social decision making. First, we tested whether the macronutrient composition of breakfast influences social decision making behavior. In a second study, we experimentally manipulated the macronutrient composition of a standardized breakfast and monitored metabolic parameters while assessing social decisions. As a primary outcome, we assessed rejection rates (as a proxy for social punishment) that target non-norm-compliant behavior in a UG (16). We hypothesized that a meal with a high carbohydrate/protein (carb/protein) ratio would induce distinct metabolic and hormonal changes that translated into different social punishment rates. We predicted that blood glucose concentrations as well as tryptophan levels would be higher in a high carb/protein compared to a low carb/protein condition. In contrast, we predicted tyrosine levels would be lower in a high carb/protein compared to a low carb/protein condition. For all other parameters we did not have an a priori hypotheses.

In study 1, we assessed the relationship between the subject's breakfast macronutrient composition and social rejection rates after the subject's natural breakfast intake. Before lunch (between 11:00 and 13:00), subjects submitted a detailed food list of their breakfast on that day. Furthermore, they also played a one-shot UG, in which they could punish a norm violator who had made an unfair offer. We computed each individual breakfast's carbohydrate and protein ratio for group subjects as high carb/protein ratio or low carb/protein ratio based on a median split. When comparing rejection rates, we observed a significant difference between groups ($x^2(1)=6.926$, $p=.011$, $phi=0.302$, Figure 1A). Within the low carb/protein group, 24% of subjects decided to reject unfair offers. In contrast, 53% of the high carb/protein group decided to reject unfair offers. A point-biserial correlation analysis confirmed this finding by indicating a positive correlation between the carb/protein ratio and rejection rates ($r_{pb}=0.22$, $p=0.03$). Of note, there were no differences between the groups for age, gender, BMI, or total energy of breakfast (see SI for more results).

Motivated by the findings of study 1, we designed a randomized, balanced, crossover intervention experiment with a double-blind design that enabled us to test for a causal relationship between the macronutrient composition of a controlled meal and rejection rates (study 2). Since our aim was to induce *physiological* fluctuations in metabolic parameters due to food consumption, we offered subjects breakfasts that differed in macronutrient composition, albeit within a range present in real life western-world breakfasts. This enabled us to assess the impact of a controlled low (50%/25%) vs. high (80%/10%) carb/protein ratio of a standard breakfast meal on subsequent rejection decisions and individual metabolic parameters.

In line with predictions from study 1, we hypothesized higher rejection rates following a high carb/protein breakfast compared to a low carb/protein breakfast. To be considered as a candidate metabolic parameter for explaining food-related behavior modifications, we required that two criteria must be met. First, the metabolic parameter should show a significant change depending on the breakfast's macronutrient composition. Second, the significant parameter change between breakfast conditions should predict significant behavioral changes across the conditions.

Confirming the finding from study 1 in a controlled experimental setting, in study 2, the macronutrient composition of breakfast significantly modulated rejection rates in response to unfair offers. The results indicated a main effect for both breakfast ($F(1,2090)=7.77$, $p=.005$) and fairness categories ($F(2,2090)=209.859$, $p<.001$). Rejection rates were significantly higher in the high carb/protein condition ($M=.69$) compared to the low carb/protein condition ($M=.60$) for unfair offers ($t(2090)=2.82$, $p=.005$; Figure 1B). Thus, subjects rejected unfair offers more often after a high carb/protein breakfast.

We then analyzed whether the macronutrient composition of breakfast had an influence on postprandial tryptophan and tyrosine levels. Ingesting the high carb/protein breakfast significantly increased plasma tryptophan ($t(15)=4.873$, $p<.001$; Figure 2A and SI) and significantly lowered plasma tyrosine levels ($t(15)=2.13$, $p=.025$; Figure 2B and S3) compared to the low carb/protein breakfast. Furthermore, peak blood glucose concentrations were significantly higher in the high carb/protein condition ($t(21)=4.675$, $p<.001$). Additionally, we documented a steeper decline after a high carb/protein breakfast ($t(21)=2.26$, $p=.035$, Figure 2C and S3).

No other metabolic parameters (insulin, testosterone, cortisol, ACTH and leptin) were significantly modulated by the different breakfasts (Table S1). Postprandial tyrosine, tryptophan, and glucose thus all fulfill the first criteria for candidate parameter underlying food-related changes in behavior.

To test whether any metabolic parameter fulfilled the second criteria, that is, to predict behavioral changes across conditions, a regression model was implemented that included the differences in metabolic parameters between conditions as predictors of change in rejection rates. In detail, the differences in AUCs (8:30-10:45) for cortisol, ACTH, insulin, leptin and FAI, the differences in AUCs (8:30-13:15) for tryptophan and tyrosine/LNAA ratios and the difference in glucose slope between 9:15 and 10:00 were used as predictors. The analysis revealed tyrosine, insulin, and cortisol as significant negative predictors and ACTH as a significant positive predictor for rejection rates in the UG (model: $R^2=.648$, $f^2=1.99$; tyrosine: $p=.012$; insulin: $p=.023$; cortisol: $p=.021$; ACTH: p=.044; Table S2). Thus, differences in tyrosine, insulin, cortisol and ACTH predict changes in rejection rates between both conditions, thereby fulfilling the second criteria for a candidate mechanism underlying food-related changes in behavior. Strikingly, only tyrosine fulfilled both criteria as its levels were significantly modulated by the breakfasts and this difference significantly predicted changes in rejection rates (Figure 2D, the correlation between changes in tyrosine and rejection rate is shown).

Finally, we checked for changes in mood across conditions to rule out the possibility that induced differences in rejection behavior are explained as a secondary consequence of a change in mood. We did not observe any statistically significant differences in mood between the conditions (PANAS negative: p=.99, PANAS positive: p=.156, SHS p=.163). Moreover, the change in rejection rates was not influenced by personality traits (Table S3).

We provided converging evidence from two studies showing that a relatively small variation in breakfast's macronutrient composition has a striking impact on social decisions. In study 1, we showed a significant behavioral difference depending on the carb/protein ratio of a subject's natural breakfast, with subjects reporting a higher carb/protein breakfast intake exhibiting higher rejection rates in a subsequent UG.

A limitation of study 1 is its restricted explanatory power concerning the effect of time and the exact macronutrient composition. Some subjects reported more than one breakfast time, since they consumed snacks after their actual breakfast. Furthermore, we only have the information about when subjects started the online questionnaire, but not when exactly they performed the UG. Additionally, not only was the computation of the macronutrient composition based on self-report, there was also a large individual difference in reported macronutrient composition. These considerations motivated us to conduct study 2, where we could control both the timing of ingestion and its exact macronutrient composition.

In study 2, we were able to go one step further than was possible in study 1 by testing the direct causality of distinct macronutrient compositions on rejection rates, while controlling time and macronutrient composition. This also allowed us to characterize the specific metabolic dynamics underlying a change in decisions. We again replicated the results from study 1 by showing that a high carb/protein breakfast increases rejection behavior, and this effect is explained as arising out of a decrease in plasma tyrosine.

Across both studies, rejection rates in the UG were higher after a high carb/protein breakfast. An equicaloric breakfast with a higher carb/protein ratio led to markedly different postprandial blood glucose and neurotransmitter precursor levels. Specifically, a high carb/protein meal caused lower tyrosine levels, higher tryptophan levels and a steeper decline in postprandial blood glucose. No other blood parameters differed significantly between conditions. The observed changes in rejection decisions correlated with several metabolic parameters, but only tyrosine fulfilled both defined criteria to be an underlying factor driving the change in behavior. First, tyrosine levels were significantly different between conditions, i.e., being lower after the high carb/protein breakfast. Second, changes in tyrosine levels significantly predicted changes in rejection rates.

The observed macronutrient-driven changes in glucose, tyrosine and tryptophan levels are in line with the literature (1, 12). Furthermore, our data shed new light on previous findings on food-related changes in metabolic and hormonal parameters and their impact on behavior. So far, food-related changes in behavior have often been explained by the ego depletion theory, implying that an overall energy (glucose) decline below optimal levels changes behavior by decreasing self-control (3, 17). However, it is important to highlight that in most studies, blood glucose was not assessed, and recent evidence indicates rather inconsistent results (18). Although we observed a significantly steeper glucose decline in the high compared to the low carb/protein condition, we did not find a direct link between glucose decline and social decisions. Altered neurotransmitter concentrations after food intake have been previously demonstrated by measuring differences in brain tryptophan and tyrosine levels engendered by food consumption (2, 9). However, a possible impact on behavior was not assessed.

Previous studies have already shown that brain tyrosine and its neurotransmitter product dopamine are involved in a variety of social decisions (19). Genetic studies indicate a link between the dopamine system and social punishment (20), suggesting a dose-dependent dopamine effect. Furthermore, fMRI studies have suggested a role for mesolimbic dopamine in social decisions (21). Dopamine neurons encode reward prediction errors, i.e., deviations between predicted and experienced reward. The UG induces robust reward prediction errors as a consequence of unexpected unfair offers (22). Thus, differences in tyrosine levels might alter rejection rates via an influence on this DA prediction error signaling.

Although suggested by previous studies, we did not find a direct link between meal-induced changes in tryptophan on subsequent punishment rates. Previous studies reported higher rejection rates after tryptophan depletion and lower rates after pharmacological increase (4, 23). Of note, in these studies, tryptophan concentrations, although associated with punishment rates, failed to significantly predict the rejection rates (4; supporting online material). Thus, it is difficult to rule out a possibility that tryptophan changes were not the causal underlying factor. An alternative explanation is that the significant changes in blood tryptophan levels in our study might not have been sufficient to cause changes in behavior.

One limitation of study 2 is its constrained generalizability. Since previous studies have shown gender differences in metabolism (24), only male subjects were included in study 2. The reported results thus only apply for men. Furthermore, the present results only apply for a very specific macronutrient composition. Although findings of study 1 suggest that results might be similar for women and for varying macronutrient compositions, the exact impact of varying macronutrient compositions as well as their effect on female metabolism and behavior need to be the focus of future studies.

In this study, we demonstrated that the macronutrient composition of food acutely influences our social decisions, showing a modulation in the dopamine precursor as the underlying mechanism. Our results shed new light on the striking relevance of food intake. This opens new perspectives on problems such as anti-social behavior as well as the global problem of poor nutrition. The latter may not only have negative consequences on physical health but also on social decisions. On that background, popular diets, as for example low carb diets, might be treated with caution. Independent of a diet's effectiveness for losing weight, it could have potential side effects on people's social behavior. By emphasizing the importance of educational and support campaigns to establish a balanced diet, our results have implications for society, economics and policy formation. Specifically, the nature of large scale food distribution, such as in kindergarten, schools and the military, would merit reconsideration. Finally, our results hint at possibilities inherent in targeted food interventions as possible additional treatments in the clinical context that might support established behavioral modification programs.

Materials and Methods

Ultimatum Game

The Ultimatum Game (UG) is a two person game in which one person (the proposer) suggests how to share a sum of money with another player (the receiver). If the receiver accepts the proposed offer, both players are paid accordingly. However, if the receiver rejects the offer, neither receives any payment. Studies show that receivers usually reject unfair offers, which is interpreted as a form of social punishment (16).

Study 1

Subjects

Eighty-seven subjects (54 woman; mean age = 23.74, *SD* = 4.40; mean BMI = 22.28, *SD* = 2.98) participated in an online survey using the online platform Soci Survey (© 2006-2015 SoSci Survey GmbH). Subjects were students of the University of Lübeck recruited via an internal mailing list. Prior to participation, all subjects were informed about the procedure, data handling and that they could stop the questionnaire at any time point. The study was approved by the local Medical Ethical Commission of the University of Lübeck.

Procedure

The online survey was accessible only between 11:00 and 13:00, and subjects were instructed beforehand to complete the survey before lunch. First, subjects received instructions about the UG and were informed that the decisions of 20 randomly selected subjects would be paid accordingly. Subsequently, subjects played a one-shot version of the UG. Here, subjects were in the role of the receiver. All subjects were told that the proposer, who participated in the online study before them, was endowed with 10€ and that the proposer decided to offer 2€ to the subject. Thus, all subjects received an unfair offer of 2€ and could decide whether to accept or reject this offer.

After the UG, subjects submitted a detailed description of all food items they consumed previously on that day (breakfast + snacks). The ratio of carbohydrates and proteins (carb/protein) as a percentage of total energy intake was calculated using the DGExpert algorithm (© 2013 Deutsche Gesellschaft für Ernährung).

Data analysis

Eleven subjects were excluded from the analyses because they indicated that they had no breakfast on the corresponding day. Therefore, subsequent analyses included the data of 76 subjects. To test whether there is an association between a subject's macronutrient composition and rejection rates in the UG, we compared the rejection behavior of subjects who had a high carb/protein ratio with those who had a low ratio (groups were determined by median split). A x^2 test was applied to compare rejection rates between groups. Additional tests were conducted to control whether groups differed concerning age, BMI, gender or total energy intake. Since age, BMI and total energy intake were not normally distributed, Mann-Whitney-U-Tests were used. To compare the gender distribution between the groups a x^2 test was applied. Furthermore, a point-biserial correlation was applied to determine the relationship between carb/protein ratio and punishment and to support the median-split analysis. For this analysis, three outliers (mean ± 2SD) were excluded and one-sided p-values are reported.

Study 2

Subjects

Twenty-four male subjects participated in the experimental study (mean age = 24.64, *SD* = 4.06; mean BMI = 22.59, *SD* = 1.82). The sample size was chosen based on previous metabolic studies (4, 25–27). Since other studies have shown gender differences in metabolism, only male subjects were included (24). Before experimental participation, every subject underwent a medical screening with a special focus on metabolic diseases. The medical screening consisted of a blood sample, a questionnaire and a complete physical examination, including a visual examination of the mouth, eyes and skin; manual palpation of the lymph nodes, thyroid gland and abdomen; manual tapping of the spinal column and kidneys; auscultation of the heart, lungs and abdomen; measurement of body weight, blood pressure and heart rate; and an electrocardiogram. The following blood parameters were examined: full blood count, glucose, liver enzymes, thyroid function, kidney function, electrolytes and blood lipids. Exclusion criteria were any abnormalities in the blood results or physical examination, any physical or psychological disease, shifted day-night rhythm, being a high-performance athlete, BMI under 18 kg/m^2 or above 25 kg/m^2, smoking, or food allergies. Prior to participation, all subjects gave written informed consent according to the Declaration of Helsinki. The study was approved by the local Medical Ethical Commission of the University of Lübeck.

Experimental Procedure

Subjects were tested in a randomized, balanced, within-subject design during two sessions separated by at least 7 days (max. 9 days). Both sessions were identical except for the macronutrient composition in the breakfast subjects had. On one day, subjects received a breakfast with a low carbohydrate and high protein content (low carb/protein condition), and on the other day they received a breakfast with a high carbohydrate and low protein content (high carb/protein condition). In the low carb/protein condition the breakfast contained 50% carbohydrates, 25% lipids and 25% proteins, and the high carb/protein condition was 80% carbohydrates, 10% lipids and 10% proteins (see Figure S1). In detail, the high carb/protein breakfast contained: 88 g 'Vital-Fit' whole-grain bread, 20 g ham, 5 g cream cheese, 30 g strawberry marmalade, 130 ml milk, 200 ml apple juice, 110 ml water, 225 g banana and 225 g apple. The low carb/protein breakfast contained: 70 g sunflower seed bread, 70 g 'Vital-Fit' whole-grain bread, 40 g ham, 30 g 'Bresso' (cream cheese), 40 g Camembert, 240 ml milk, 200 ml water, 250 ml yogurt and 120 g banana. Both breakfasts had the same total amount of calories (850 kcal), and subjects had to complete the whole breakfast.

After arrival at the research unit at 8:00, an intravenous catheter was inserted into a vein of the participant's non-dominant distal forearm and at 8:30 the first blood sample was obtained. At 8:45 subjects received breakfast in a single room according to the respective high carb/protein or low carb/protein condition. From 9:00 till 10:45, blood samples were drawn in 15 min intervals with additional blood samples at 11:30 and 13:15 (see Figure S2). During the whole procedure subjects could either lay in bed or sit on a chair but were not allowed to leave their room or perform any type of physical exercise.

At 12:00, subjects were guided to a different room where they completed a test battery including the UG, the interpersonal reactivity index (IRI, 28), the social value orientation (SVO, 29), the positive affect negative affect scale (PANAS, 30), the subjective happiness scale (SHS, 31), the state-trait anxiety inventory (STAI, 32) and the behavioral inhibitory system/behavioral approach system (BIS/BAS, 33). These assessments were performed at 12:15, since the maximum difference in neurotransmitter precursor concentrations between conditions was expected to be present 3.5-4 h after the food intake (2, 4). Subjects first received written instructions on the UG and were asked to answer a set of comprehension questions before starting the game.

In study 2 all subjects were in the role of the receiver and played 48 trials of the UG with 48 different proposers via a computer interface. In each trial, subjects sequentially observed the picture of the proposer (1500 ms), the endowment of the proposer (1500 ms) and the offer of the proposer (3000 ms). By pressing one of two buttons, subjects could indicate whether they accepted or rejected the offer. Their response was highlighted on the screen (see Figure S3). Proposer pictures were randomly matched with the offers. Eight 'fair', eight 'medium' and eight 'unfair' offers were all presented twice in a randomized order. The 'fair' offers ranged between 40% - 50% of the proposer's endowment, the 'medium' offers between 27% - 33% and the 'unfair' between 18% - 22%. Thus, in different trials the same amount could either be a 'fair' or an 'unfair' offer depending on the proposer's endowment. This way we could investigate fairness independent of monetary reward. The dependent variable was the punishment decision (yes or no) with respect to rejected 'fair', 'medium' and 'unfair' offers. Subjects were told that the proposers in the picture previously participated in the experiment and that they would receive their money according to the receiver's decisions. Each trial started with a picture of the alleged proposer. Half of the pictures showed male and the other half showed female faces.

After completing the UG, subjects again filled in the respective questionnaires and were guided back to their room where the last blood sample was obtained (13:15). Subjects received a fee for their participation in the whole study. They were told that, in addition, one out of all trials of the test battery of both sessions would randomly be picked and payed out after the second session.

Blood samples

Twenty-two plasma amino acids were determined from blood samples drawn at 8:30, 10:45, 11:30 and 13:15. From the blood samples drawn at 8:30, 9:00, 9:15, 9:30, 9:45, 10:00, 10:15, 10:30 and 10:45, the following parameters were determined: glucose, testosterone, sex hormone-binding globulin (SHGB), cortisol, adrenocorticotropic hormone (ACTH), leptin and insulin. All blood samples were immediately centrifuged at 4 °C and stored at -80 °C until analysis. Measurement of plasma amino acids was performed according to the method of Harder, Koletzko and Peissner (34). Harder and colleagues combine precipitation, derivatization and chromatographic separation to determine all proteinogenic amino acids, citrulline and ornithine. For a detailed description, see (34).

Blood glucose was measured by an enzymatic-amperometric method (EKF Diagnostics, Barleben, Deutschland, CV ≤ 1.5%). Leptin concentrations were assessed by a radioimmunoassay (RIA Kit, EMD Millipore, Missouri, USA, within-CV < 8.3%, between-CV < 6.2%). Insulin, cortisol, ACTH, and SHGB were assessed by immunoassays (Immulite 2000, Siemend Healthcare Diagnostics, UK). The assessed within- and between-assay variations were as follows: insulin within-CV 3.3-3.9%, between-CV 4.1-5.0%; SHGB within-CV 2.5-2.7%, between-CV < 5.2%; ACTH within-CV < 8.7%, between-CV < 10.0%; cortisol within-CV < 5.2%, between-CV < 6.8% and testosterone within-CV 8.3-7.2%, between-CV 9.1-8.2%.

Data analysis

Two subjects were excluded from the UG analyses, one owing to technical recording problems and one because he was aware of the study design and hypothesis before participating, yielding a final sample size of 22 subjects.

First, we tested for a difference in rejection rates between the two breakfast conditions using a mixed logistic model to analyze the effect of macronutrient content on UG decisions. Rejection rates were used as dependent variable, breakfast (high carb/protein and low carb/protein) and fairness category (fair, medium and unfair) were used as fixed effects, and a random intercept was allowed for each subject. Corresponding post hoc tests were applied to investigate the exact relationship between the factors.

Second, the influence of breakfast's macronutrient composition on tryptophan and tyrosine levels was examined. Ratios between plasma concentrations of tryptophan and tyrosine and the other LNAAs were used as a proxy for brain tryptophan and tyrosine levels and ultimately brain serotonin and dopamine levels (2, 9). One subject was excluded from this analysis due to technical problems. Furthermore, blood data of five participants could not be analyzed for every time point. Differences in area under the curve (AUC) values (8:30-13:15) of tryptophan- or tyrosine/LNAA ratios were tested using dependent sample t-tests (one-sided tested according to a priori hypothesis). To check at which time points the values differed, repeated measures ANOVA was conducted with the factor's time (10:45-13:15) and condition as within-subject factors and either tryptophan- or tyrosine/LNAA ratio (corrected for baseline) as the dependent variable. Corresponding post hoc tests were applied to investigate the exact relationship between factors.

Next, we tested for differences in glucose drop between conditions. Since the decline in blood glucose was shown to be a better predictor for hypoglycemia symptoms (35), we used a dependent sample t-test to test for differences in glucose decline between 9:15 and 10:00. A repeated measures

ANOVA with the within-subject factor's time (8:30-10:45) and condition (respective breakfast condition) was used to address differences in blood glucose over time. Corresponding post hoc tests were performed to investigate the exact relationship between the factors.

Moreover, we analyzed the effect of the respective condition on cortisol, ACTH, insulin, leptin concentrations and free androgen index (FAI). FAI as the ratio of total testosterone and SHBG x 100 is used as a proxy of free (bioactive) testosterone. Differences in AUC (8:30-10:45) of cortisol, ACTH, insulin, leptin and FAI were tested using dependent sample t-tests. To test at which time points values differed between the breakfast conditions, a repeated measures ANOVA was conducted with the factor's time (8:45-10:45) and condition as within-subject factors and either cortisol, ACTH, insulin or FAI (corrected for baseline) as the dependent variable.

To test if any of the parameters had an influence on rejection rates, a regression model including all blood parameters as predictors and rejection rates as the dependent variable was applied. In detail, changes in the parameter values (differences in AUCs (8:30-10:45) for cortisol, ACTH, insulin, leptin and FAI; AUCs for tryptophan- and tyrosine/LNAA ratios (8:30-13:15); glucose slope between 9:15 and 10:00) and rejection rates between both breakfast conditions (high carb/protein minus low carb/protein) were used for this analysis. Furthermore, we tested whether mood was influenced by the different conditions when comparing the PANAS (because it is not normally distributed, a Wilcoxon test for dependent samples was used) and SHS (t-test for dependent samples) scores. All questionnaire results were corrected for multiple comparisons, resulting in a Bonferroni corrected significance threshold of .016.

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Figure legends

Figure 1 Decision making depends on breakfast carb/protein ratio A) In study 1, subjects were grouped in low vs. high carb/protein groups depending on the macronutrient composition of their breakfast on that morning. Yellow bars indicate the fraction of subjects who decided to reject. Subjects with high carb/protein ratio breakfasts showed significantly more rejection behavior (*p<.05). B) Differences (high carb/protein minus low carb/protein condition) in rejection rates separated for fairness categories (fair, medium, unfair) during the UG in the intervention experiment (study 2). Subjects showed an increase in rejection rates after a high carb/protein-ratio breakfast compared to after a low carb/protein-ratio breakfast. The values indicated are mean changes (±SEM,*p<.05).

Figure 2 Macronutrient composition-dependent changes in postprandial tryptophan, tyrosine and glucose and the correlation of tyrosine with rejection rates Blue lines indicate low and yellow lines indicate high carb/protein condition for (A) tryptophan/LNAA, (B) tyrosine/LNAA and (C) glucose values (±SEM in shadowed area, * p<.05). For visualization purposes, the data points were interpolated. (C) Shadowed area represents the time window of glucose decline, which significantly differs between the conditions. (D) Triangles indicate single data points for change in rejection rates and change in tyrosine/LNAA values between high vs. low carb/protein conditions.