Metabolic state as a modulator of neural event-related potentials for food stimuli in an implicit association test

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ABSTRACT

The Implicit Association Test (IAT) has become a ubiquitous measure of implicit associations or preferences in several fields of research, including research related to food choices. The neural dynamics of the IAT have been explored in several contexts, but in a food-related IAT with stimuli of natural motivational value they are yet to be studied. Additionally, the effect of metabolic state on them is poorly known.

The present study examined the event-related potentials (ERP) in healthy non-obese females (n = 32) while they performed a food-related IAT in two sessions, in a fasted state and after a meal.

The results showed differences in the ERP components N400, P3 and LPP by congruence categories. Additionally, the individual N400 and LPP deflections correlated strongly with individual IAT effects. ERP deflections were weaker in the fasted state than after the meal despite greater implicit hedonic motivation towards food in the fasted state.

In conclusion, the results suggest that ERPs reflect the IAT effect. The N400, P3 and LPP components were evoked in a food-related IAT in a similar way observed in IAT tests in other contexts, reflecting a difference in meaning and motivation between congruence categories. The strong correlations of individual IAT effect with individual N400 and LPP deflections further suggests that the food-related IAT effect strength reflects the size of implicit food bias seen in neural deflections. Moreover, fasting increased implicit hedonic motivation towards food, but likely reduced cognitive resources at the same time. This could have made it harder to determine the value of novel, task-relevant stimuli, whereas it became easier postprandially and with practice.

1. Introduction

Food is a natural source of reward and as such a motivator explaining and driving much of human action. The anticipated reward of food attracts our attention, which can be detected as a change in physiological activity such as neural deflections and can be modulated by homeostatic needs [1,2]. Furthermore, in recent years the dualistic nature of food reward, involving both implicit and explicit processing, has drawn interest [3]. Explicit processes of food reward are considered to be consciously observed, whereas implicit processes are not always experienced consciously [3]. Psychological and neurophysiological methods to assess implicit and explicit processes are available, such as the Implicit Association Test (IAT) [4] and electroencephalography (EEG). These methods can broaden our understanding of our motivational decision-making processes and the effect of metabolic state to it.

The IAT was designed to assess implicit preferences in a choice situation between two target categories (e.g., food vs. non-food) and two associated evaluations or actions (in this case, approach vs. avoid) [4,5]. Response time difference between congruent ('Food—Approach' and 'Non-food—Avoid') and incongruent ('Food—Avoid' and 'Non-food—Approach') categorization situations produces the IAT effect, or D-score, which is considered to measure how strongly the concepts are...
associated in memory [4,6]. When designing the IAT, researchers formulate a hypothesis that defines which categorization situations are predicted to be implicitly congruent and which as implicitly incongruent, and name these situations then accordingly. However, the result of the actual IAT test reveals the true direction of congruence. A positive IAT effect is an indication of stronger association towards the congruent concept pair compared to the incongruent pair, as chosen by the researchers. The critical blocks of the IAT test used to calculate the IAT effect include dozens of trials and therefore a single categorization event has only a minor effect on the overall IAT score. The test has been used, for example, to evaluate self-esteem [7], stereotypes [8] and political behavior [9] as well as associations within various food contexts [10–14].

Originally, IAT was designed to assess implicit evaluations (e.g. with “positive” vs. “negative” attribute categories) [4,5]. Recently, the IAT has been modified to identify motivational tendencies towards objects by using “approach” and “avoid” attribute categories [15–17]. This IAT variant has been used for example in alcohol-related [15] as well as in food contexts [17,18]. Kraus and Piquras-Fiszman [17] assessed implicit has been used for example in alcohol-related [15] as well as in food contexts [17,18]. Kraus and Piquras-Fiszman [17] assessed implicit associations towards food products comparing motivational (“approach” vs. “avoid”) and evaluative (“positive” vs. “negative”) attribute categories in two separate IAT tests. The evaluative IAT did not reveal clear differences in preferences between sandwiches and sweets. However, the result of the motivational IAT were in line with the results of explicit desire ratings between the food products in both hungry and reduced-hunger groups. The authors suggested that using “approach” and “avoid” attribute categories would be a sensitive method to assess implicit motivational responses towards food, whereas an evaluative IAT would be better suited to assess implicit liking.

It is still somewhat unclear whether the IAT captures implicit or explicit processes [19]. Therefore, attempts have been made to identify the mechanisms contributing to the IAT effect. Due to its high temporal resolution, electroencephalography (EEG) is one of the methods used to capture the time-course of neural processing during the IAT categorization events. These events can be seen as distinct stimuli or events that evoke neural responses, which are detected as event-related potentials (ERP) by time locking the events to the EEG. Comparison of ERPs during the first second following the stimulus presentation between congruent and incongruent situations can reveal differences in neural processing related to the IAT effect.

The components of ERP are usually named according to their polarity (N (negative) and P (positive)) and by either their order (e.g., N1, P2) or peak latency (e.g., N400 is a negative-going component centered around 400 ms), although some exceptions to this convention exist (e.g. LPP or late parietal positivity) [20]. In a visual stimulus-processing context, certain late (>300 ms) ERP components have been demonstrated to reflect neural processing related to stimulus salience or task relevance. The P3 component has been associated with stimulus evaluation and categorization, attentional resource allocation and memory processes (for reviews, see [21,22]). The stimuli that initiate a P3 activity are varied, but they seem to be always motivationally significant. The LPP (late parietal positivity) is a component related to the P3, reflecting sustained attention towards motivationally salient stimuli [23]. Further, the N400 ERP components have been associated with conflict monitoring and processing of semantics and meaning (for reviews, see [24,25]).

To our knowledge there are no studies examining ERPs during a food-related IAT, although the neural dynamics of the implicit associations in an IAT have previously been studied in other contexts. However, there is no consensus on which cognitive processes should be expected to be induced during an IAT task, regardless of context. Exploratory IAT studies using event-related potentials (ERP) have found that N2, P3, N400 and LPP components differ by the target categories (e.g. self-positive/self-negative [26], natural/built environment [27], gay/straight [28]). On the other hand, some IAT studies have discovered the N2 and N400 components to be modulated by the congruence categories of the IAT [26,28].

Approaching food and maintaining motivation-related associations towards food in memory is natural, as food is necessary for human survival. Whereas individual food items may not explicitly be as sought after as others, as a category food is more desirable than more neutral, everyday objects on an implicit level and attracts more attention [29]. Outside the IAT context, passive-viewing ERP studies have found differences in the P3 and LPP components between food and non-food stimuli [30–34], suggesting a greater motivational attention towards food stimuli. Therefore, it is of interest to find out whether similar neural activity can be found in a food-related IAT as has been found in these earlier food-related ERP-studies. Hunger modulates our attention and evaluative motivation to food. Food-related IAT studies (without ERPs) [35,36] using food words as stimuli have discovered greater reaction time difference between the test categories (food/non-food words as targets + pleasant/unpleasant attribute categories) in a fasted state compared to a postprandial state. Outside the IAT context, metabolic state alters also ERP components in passive-viewing food studies [32,34,37].

Given the lack of electrophysiological studies on the IAT effect in a food context, the aim of this study was to investigate whether differences in the IAT congruence categories and the IAT effect associate with the amplitudes of ERP components describing stimulus evaluation, motivational attention and conflict monitoring. In addition, we examined the effect of metabolic state (i.e. fasted vs. fed) on the neural representations of implicit preferences for food. Our hypothesis was that the later ERP components P3, N400 and LPP are modulated during the IAT by both event congruence and the metabolic state of the participants. The components were expected to be more positive in the congruent condition and larger (P3 and LPP more positive, N400 more negative) in the fasted condition.

2. Participants and methods

2.1. Participants

A total of 32 healthy females participated in the study (Table 1). The inclusion criteria of the study participants were age between 20 and 40 years and body mass index (BMI) between 19 and 29 kg/m². Exclusion criteria were as follows: Food allergies or intolerances, restrictive diet (e.g. vegetarian, gluten-free diet), frequent breakfast skipping, marked changes in diet during the past six months to lose weight, medication (except oral contraceptives), chronic disease (e.g. diabetes, eating disorder, celiac or neurological disease), smoking and male sex. Participants were recruited via internet-based calls within the students and personnel of the University of Eastern Finland, Savonia University of Applied Sciences and Kuopio University Hospital. A compensation of 50 euros was provided to all participants.

The study was carried out in accordance with the guidelines laid down in the Declaration of Helsinki, and the Ethical Committee of Northern Savo Hospital District, Kuopio, Finland approved all procedures involving human participants. Written informed consent was obtained from all participants.

| Characteristic                        | Mean (SD) | Min–Max |
|--------------------------------------|-----------|---------|
| Age (years)                          | 24.3 (5.5) | 20.0–40.0 |
| Weight (kg)                          | 64.7 (7.3) | 50.6–83.1 |
| Height (cm)                          | 168.2 (7.1) | 153.7–184.6 |
| Body mass index (kg/m²)              | 23.0 (3.0) | 19.2–29.3 |

SD, standard deviation.
2.2. Study design

Before participating in the study, volunteers were interviewed to confirm their eligibility to the study. At the end of the screening interview, study procedure and measurements were explained to the volunteers at general level to familiarize them with the study protocol. However, due to the nature of implicit responses, the detailed objectives of the study were not revealed to the volunteers, since prior information could have likely affected the responses and hence the reliability of the results [11,38].

Participants were instructed to maintain their habitual diet, exercise routines and sleep habits as constant as possible during the previous days before the study visit, refrain from heavy exercise 12 h before the study visit, and avoid alcohol consumption for 24 h before the study visit. At the beginning of the visit, participants' height and weight were measured, and the duration of fast and sleep and alcohol consumption during the previous day were checked by an interview.

Study visits were conducted at the Laboratory of Sensory Science of the Institute of Public Health and Clinical Nutrition at the University of Eastern Finland between 9:00 and 13:00 h. Each visit included two computer-based test sessions; the first one was performed after an overnight (10–12 h) fast (fasted state) and the second one 30 min after a pizza lunch of participant's choice (fed state) (pizza options: Hawaii, Tuna, Mozzarella and Vegetable; Dr. Oetker, Suomi Oy, Helsinki, Finland). During the 30 min, between the end of the pizza meal and the beginning of the second test session participants could read, play games or browse the Internet. Participants rated their subjective sensations of appetite (i.e., hunger, desire to eat, satiety, and fullness) on a visual analogue scale (VAS; 0–10 cm, where 0 = not at all and 10 = extremely) before and after the lunch, i.e. in the fastest and fed state.

2.3. The implicit association test, IAT

The IAT test was run by the Inquisit software (Inquisit 4.0.5.0, Millisecond Software, Seattle, WA, USA) and used to examine implicit associations between food and non-food items. The IAT test included two binary categorization tasks, one target (food vs. non-food item) and one attribute (approach vs. avoid) category pair, which were combined in an association-congruent (food – approach and non-food item – avoid) and association-incongruent (food – avoid and non-food item – approach) way. The standardized reaction time difference between the congruent and incongruent categorization events compiled as the IAT effect, or D-score, which is considered as an implication of a person's implicit bias. A positive IAT effect is interpreted as an indication of stronger association between the congruent concept pairings compared to the incongruent pairings. The IAT effect score has a possible range of −2 to +2, which indicates the strength and the direction of the association (−0.15 < D < 0.15 = little to no, D > 0.15 or D < −0.15 = slight, D > 0.35 or D < −0.35 = moderate, D > 0.65 or D < −0.65 = strong association). The raw IAT data were processed with a standard procedure in the Inquisit software to obtain the final IAT effect scores [6]. Due to the comparative nature of the IAT test, the resulting IAT effect scores cannot be interpreted as absolute preferences, but as relative ones between the target categories.

The test included 16 different target stimuli, 8 photographs for both target categories selected from a set of previously taken photographs shown in Fig. 1 [39]. The food and non-food item photos were matched in shape, colour and overall arrangement. All foods and non-food items were presented on a 15.6-in. screen, with a resolution of 1920 × 1080, on a grey background. Words (verbs in Finnish) describing the attribute categories were used as attribute stimuli, of which half indicated approach-related (aspire, seek, favor, desire, choose, long for, need, take) and half avoid-related (refuse, avoid, restrict, reject, abandon, watch out, evade, withdraw) words. Both the target and attribute categories were presented in the top left and top right corners of the screen, and remained on the screen during the IAT test. Stimulus photos and words were displayed successively in the center of the screen. Participants were instructed to categorize the stimulus photos and words as fast and accurately as possible by pressing one of two assigned response keys (left ‘E’ or right ‘I’) according to the category labels, while their individual performance (reaction time and accuracy of the categorization (error rate)) was measured. The stimuli were displayed until the participant pressed a key and the interval between trials was 250 ms for all trials. Trials with a reaction time of > 10,000 ms were not included in further analysis. For incorrect responses they were given feedback by an ‘X’ in the middle of the screen. A participant's error rate of > 10% was an exclusion criterion for the analysis of the IAT test results. One participant was excluded from the analysis.

The IAT test followed a fixed block structure and included seven different blocks divided into practice (five blocks) and test trials (two blocks) (Fig. 2). After the separate practice blocks for target, attribute and their combination (20 trials in each), the first combined test block with 40 trials was presented. Then the categorization task changed between the blocks, continued with two practice blocks (20 trials) and ended with the second test block (40 trials). The order of the association-congruent and association-incongruent blocks was counter-balanced over participants. The duration of each block varied, as it was determined by the participant’s reaction speed. Average duration of a single IAT was 2 min 50 s and with subjective sensation evaluations, the duration was 5 min on average.

2.4. Psychophysiological measurements and data analysis

The NeurOne monitoring system (Mega Electronics Ltd., Kuopio, Finland) was used to record scalp EEG. The EEG signal was digitized with a 500 Hz sampling rate from 64 Ag-AgCl electrodes mounted in an elastic cap (extended 10–20 system). Impedances were reduced to under 5 kΩ for all electrodes. After recording, signals were filtered with a bandpass of 1–40 Hz and down-sampled to 200 Hz. Removal of artefacts caused by blinks or eye movement was made using a regression algorithm. Electrodes T9 and T10 were used as a linked mastoid reference. Stimulus-locked epochs of −100 to 1000 ms relative to the stimulus presentation were extracted. All epochs containing signals exceeding 50 mV were rejected before averaging. For the events during the IAT test and subsequent picture evaluations, average ERP waveforms were calculated for each electrode and grand average waveforms across all participants. The 100 ms pre-stimulus time window served as a baseline, and the amplitude of each ERP component was calculated as a difference to this baseline. Each participant’s all waveforms of a certain IAT trial (e.g., food – approach) were compared to each other and waveforms considerably different from the others (e.g., because the participant’s thoughts were wandering) were discarded from further analyses. Altogether 5.8% of all ERP waveforms were discarded this way. ERP components have spatially different neural source locations and thus have different distributions across electrodes. Therefore, we divided electrodes into three clusters, parietal (Pz, P1, P2), central (C3, C4, Cz, C1, C2) and frontal (F3, F4, Fz, F1, F2). Based on previous IAT-ERP and food-ERP studies [26–28,31–34], we identified three ERP components from the grand average responses for further investigation: P3 was extracted from 300 to 400 ms in the parietal cluster, N400 from 400 to 500 ms in the frontal, central and parietal clusters and LPP from 500 to 700 ms after the stimulus presentation in the parietal cluster.

Data analysis was carried out in Matlab (version 9.3; MathWorks, Natick MA, USA) using custom-made code.

2.5. Statistical analysis

The effects of metabolic state on subjective ratings and reaction times as well as the effect of congruence on reaction times were tested using paired-samples t-tests. Statistical analyses were performed separately for each ERP component of interest. To investigate the effect of metabolic state and the congruent and incongruent categories of the
IAT on measured variables, all mean amplitude ERP values were submitted to a 2 (congruence: congruent, incongruent) × 2 (metabolic state: fasted, fed) ANOVA for repeated-measures. Interrelations between ERP response differences (congruent–incongruent) and individual IAT effect scores were analyzed by non-parametrical Spearman correlation analysis to take into account the possible distorting effect of outliers. However, parametrical Pearson correlation analysis was also concluded in comparison. Unless otherwise specified, the results are reported as means ± standard deviation (SD) with a value $p \leq .05$ (2-tailed) as a criterion for the statistical significance.

The Matlab Statistics and Machine Learning Toolbox (version 11.2; MathWorks, Natick MA, USA) was used for conducting statistical analyses.

Fig. 1. The 16 photographs used as target stimuli in the IAT, 8 from each target category [39].

Fig. 2. Examples of the congruent (top row) and incongruent (bottom row) categorization task situations. The correct response category in each situation is indicated by a red box and the generated association between the targets and attributes is indicated by a pale blue box (the boxes are not displayed in the actual IAT session). Stimulus photos were categorized by corresponding target categories (“Food” or “Non-food”) and stimulus words were categorized by corresponding attribute categories (e.g., word “aspire” to category “Approach”, word “abandon to category “Avoid”). Words were presented in Finnish. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
3. Results

3.1. Explicit measures: appetite ratings

As expected, the participants’ subjective appetite ratings changed significantly from the fasted to the fed state, which indicated a significant change in the metabolic state (Table 2). The levels of hunger and desire to eat were higher whereas satiety and fullness levels were lower in the fasted state compared to the fed state.

3.2. Behavioral measures: IAT

In the fasted state, reaction time (RT) were shorter in the congruent than in the incongruent category (Table 3). This difference was present also in the fed state, even though the RTs in both categories were shorter compared to the fasted state. The RT differences reflected the group level average IAT effect scores, which were positive in both metabolic states, indicating that there was a group level preference for food over non-food items. This preference was moderate (D > 0.35) in the fasted state compared to the fed state. In the statistical analyses for the analyzed ERPs, no significant interaction effect of congruence × metabolic state was found, indicating that the metabolic state effect did not have an influence on the congruence effect and vice versa. Therefore, in the following sections only main effects are described in more detail.

N400: The predicted congruence main effect was observed in the central (F1,31 = 6.01, p = .020) and parietal (F1,31 = 28.46, p < .001) clusters, with larger (relatively more negative) amplitudes in the incongruent compared to the congruent category. However, no congruence effect was seen in the frontal cluster (p = .46). Furthermore, the predicted main effect of the metabolic state was observed in central (F1,31 = 8.96, p = .005) and parietal (F1,31 = 30.41, p < .001) clusters, with larger (relatively more negative) amplitudes in the fasted compared to the fed state. No metabolic state effect was found in the frontal cluster (p = .73).

Additionally, we examined the possible effect of consecutive components’ amplitudes to each other [20]. To investigate whether the parietal N400 might have been affected by the previous P3 component, we ran an additional paired t-test on the congruent-incongruent and fasted-fed differences on N400-P3. The comparative difference between N400 and P3 amplitudes were significant by metabolic state (p < .001), but not by congruence (p = .77).

P3: Analysis of the congruence effect in the parietal P3 component revealed a significant difference between the congruence categories (F1,31 = 23.52, p < .001), with larger (more positive) amplitudes for the congruent category. A main effect for metabolic state was discovered as well (F1,31 = 4.37, p = .045), with larger (more positive) amplitudes in the fed compared to the fasted state.

LPP: The parietal LPP ERP component also displayed a congruence main effect (F1,31 = 25.71, p < .001), with larger (more positive) amplitudes in the congruent category. Further, a main effect for the metabolic state was found (F1,31 = 28.17, p < .001), such that amplitudes were larger (more positive) in the fed state. Similarly to the N400, the LPP might have been influenced by the temporally previous parietal N400 component. An additional paired t-test was performed on the congruent-incongruent and fasted-fed differences on LPP-N400. The comparative difference between LPP and N400 amplitudes were found to be non-significant by metabolic state (p = .39) and by congruence (p = .12).

3.4. The effect of individual implicit association

The Spearman correlation analysis between the IAT effect values and ERP measures (Fig. 5) revealed the following interconnections:

N400: The central N400 amplitude difference (congruent-incongruent) was found to have a significant positive correlation with the IAT effect values in the fasted state. For the parietal N400

Table 2
Ratings of subjective appetite sensations (mean (SD)) in the fasted and fed states (n = 32 females).

| Subjective sensation | Fasted state | Fed state | p-value* |
|----------------------|-------------|-----------|----------|
| Hunger               | 5.2 (2.1)   | 0.5 (0.7) | p < .001|
| Desire to eat        | 6.0 (1.9)   | 1.6 (1.5) | p < .001|
| Satiety              | 2.4 (2.3)   | 8.6 (0.8) | p < .001|
| Fullness             | 2.0 (2.0)   | 7.9 (1.3) | p < .001|

* Paired samples t-test.

Table 3
Average reaction times (mean (SD), in milliseconds) and IAT effect values from the IAT test.

| Statistics           | Metabolic state | Overall mean | Congruent | Incongruent | p-value |
|----------------------|-----------------|--------------|-----------|-------------|---------|
| Reaction time        | Fasted          | 930 (460)    | 860 (450) | 1000 (460)  | p < .001|
|                      | Fed             | 770 (280)    | 740 (260) | 810 (290)   | p < .001|
| p-value              |                 |              | p < .001  | p < .001    |         |
| IAT effect           | Fasted          | 0.47 (0.40)  | 0.33 (0.35) | p = .03   |         |
|                      | Fed             |              |           |             |         |

SD, standard deviation.

*p Paired samples t-test.
congruent–incongruent difference, there was a strong positive correlation with the IAT effect both in the fasted and in the fed state. No correlations were found for the frontal N400.

P3: No correlations were found between the P3 and the IAT effect in either the fasted or the fed state.

LPP: The LPP difference (congruent–incongruent) was found to have a significant positive correlation with the IAT effect in the fed state.

For comparison, we concluded a parametric Pearson correlation analysis, which in addition to the significant results of the Spearman’s correlation revealed a significant positive correlation with the LPP difference and the IAT effect in the fasted state ($p = .014$).

4. Discussion

The present study examined how the ERP components are modulated by the congruence categories of the IAT and whether there is a relationship between the ERP measures and the IAT effect, i.e. the IAT effect. Furthermore, this study examined the effect of metabolic state, i.e. the influence of fasted and fed state on food-related implicit preferences and ERP markers measured during the IAT. As hypothesized, the main ERP amplitudes were modulated by both event congruence and the metabolic state of the participants, being more positive in the congruent categories and in the fed state.

4.1. ERP components and IAT effect

The negative central-parietal N400 component was larger in the present study in the incongruent compared to the congruent category. This result is in line with the processing of meaning and conflict sensitivity qualities related to the N400 component (for review, see [25]). Similar results were also reported in previous IAT-ERP studies surveying neural bases of other associations such as self-positivity [26] and gay/straight bias [28]. The result was interpreted by Williams and Themanson as reflecting the incongruence in meaning between the target and attribute categories.

P3 amplitudes increased in the congruent IAT trials compared to the incongruent trials in the present study. The parietal P3 is known to reflect stimulus evaluation and categorization, and its amplitude increases by arousal level and the task-relevance or other motivational significance of the stimulus (for reviews, see [21,22]. This finding is in line with the results of the available ERP studies that found a parietal P3 enhancement in visual food cue studies [30–32,34,40], and attitude–association IAT tests [26,27,41]. Food is a motivationally important stimulus and via the IAT also reflects in task-motivation that therefore evokes the P3 component.

The parietal LPP component was higher in congruent compared to incongruent categories in the present study. Somewhat similarly to the P3, the LPP reflects sustained attention towards motivationally salient stimuli and is involved in memory formation [23]. Higher amplitudes...
for arousing stimuli have been construed as indicating enhanced memory processing performance for these stimuli. Several IAT-ERP studies have found modulation by congruence in the LPP (or an LPP-like deflection) with target stimuli related to race [42], sexual orientation [28] and gender [43].

We found several significant correlations between individual IAT effect and congruence category related ERP amplitudes. The N400 and LPP amplitude differences (congruent - incongruent) were stronger in individuals with higher IAT effect. This suggests that individuals showing pronounced implicit preference towards food showed stronger LPP amplitudes in congruent compared to incongruent situations and larger N400 amplitudes in incongruent compared to congruent situations. In other words, stronger food bias evokes stronger conflict monitoring towards avoiding food objects as well as greater effort in constructing a meaning for combining such options, both seen in the N400. The strength of food bias also generates increased motivation towards food stimuli, seen in the LPP. This suggests that food bias strength observed in the IAT effect dominates ERP differences.

These results are also in line with the results reported in previous IAT research in other contexts. Schindler et al. [44] observed in a doping attitude IAT study a similar correlation as in the present study between the IAT effect and the parietal LPP. On the other hand, Williams and Themanson [28] and Wu et al. [26] compared reaction time differences (incongruent-congruent) to ERP amplitude differences (congruent-incongruent) and reported reverse U-shaped correlations for reaction time differences and ERP components (N400 and LPP; and P3, respectively). However, it remains unsolved whether the direction of correlation differs due to the nature of the IAT or variations in the statistical methods.

In summary, these results indicate that on the group level, the N400, P3 and LPP components are evoked in a food-related IAT task in a similar way to IAT tasks reported in other contexts. Additionally, on the individual level, the N400 and the LPP correlated strongly with the IAT effect, suggesting that the IAT effect reflects neural deflections of implicit food bias.

4.2. Effect of metabolic state

Participants described themselves to be significantly hungrier before the meal than postprandially (Table 2), which indicated that a change in the metabolic state had occurred. As motivation towards food was predicted to be higher in the fasted state, fasting was hypothesized to modulate ERP components sensitive to motivationally salient stimuli (P3, LPP) and associated with processing of meaning and conflict monitoring qualities (N400).

Surprisingly, the motivation-related ERP components (P3, LPP) were significantly stronger in the fed compared to the fasted state. On the other hand, compared to the fed state, response-based measures, i.e. IAT reaction times and the IAT effect, showed a stronger implicit preference of the participants towards food when fasting (Table 3), which

Fig. 4. Changes in the studied ERP components in individual participants by congruence category (top row) and metabolic state (bottom row). The blue lines describe decrease and the red, dashed lines increase in ERP amplitudes. In the negative-going N400 component, a smaller amplitude describes a larger component, whereas in the positive-going P3 and LPP components a larger component is described by a larger amplitude. The blue bars on the sides represent the grand mean amplitudes with standard deviations. CON = congruent, INC = incongruent, FAS = fasted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
is in line with previous literature [35,36]. This change in the implicit preferences seemed to be opposite to those seen in the P3 and LPP components, initially suggesting that metabolic state does not have a parallel effect on presumed behavioral and ERP indices of implicit preferences towards food. However, in non-IAT studies observing the effect of fasting to food-related ERPs, viewing food stimuli have elicited stronger ERPs in a fasted compared to a fed state contrary to the ERP results seen in the current study. Increases have been detected in parietal P3 [30,32,34,37] and LPP components [31,37]. These results would seem to disagree with the ERP results seen in this study and suggest that the motivation towards food stimuli is increased in a deprived state.

The N400 component was larger in the fasted state. This likely reflects heightened conflict monitoring or increased meaning processing [25]. To our knowledge, the effect of metabolic state to the N400 component has not been previously studied, making this a novel finding.

There are several potential explanations for the differences in the results between the current study and the studies described above. First, implicit preferences are comprised of hedonic and cognitive neural systems, which influence choices uniquely and are modified differently by availability of cognitive resources [45–47]. Second, the IAT is cognitively more demanding than passive viewing paradigms [48], modifying motivation-related ERPs differently. Third, fasting reduces cognitive resources and affects the perceived difficulty of the cognitive task at hand, which in turn have an effect on the implicit hedonic and cognitive bases of choice seen in task performance (for review, see [49]), IAT effect [35,36] and neural activation [50–52]. On the other hand, in the present study participants completed the same IAT test both before and after a lunch, which may result in a better performance and altered neural deflections during the second IAT task simply due to a learning effect and therefore participants likely performed the task more efficiently [53].

In the present study, the implicit preference to food, as measured by the IAT effect, was stronger in the fasted state than postprandially (Table 3) and therefore produced results counterintuitive to those seen in neural activity, which implied a higher arousal in the fed state (Fig. 3). Trendel and Werle [45] found that overall implicit attitudes to food are driven not only by a hedonic basis of implicit attitudes, but also by an automatic cognitive basis distinct and independent from the hedonic component, which has also been found in other contexts [47,54]. This finding is in accordance with dual process models employed in the field of social psychology (see [55]), which propose an existence of automatic and controlled processes that contribute in behavior. Trendel and Werle also found the two systems to react differently under high and low cognitive load, with the food's palatability driving food choices under high load and the cognitive implicit basis having a greater impact when greater cognitive capacity was available. This result was in agreement with the ‘attentional myopia’ model of Mann and Ward [46] stating that restricted attention can lead to most salient cues stealing focus. Considering that in this study the fasting effect influenced the implicit preferences, as shown in the IAT effect, differently to those seen in the motivation-related ERPs (P3, LPP), it might be that the implicit hedonic and cognitive processing operated differently under the load of fasting.

In the present study, the effect of fasting to ERP amplitudes was opposite to those observed in previous food-related ERP studies [32,34,37]. However, in contrast to this study, these studies implemented mainly passive viewing paradigms, which might have required less concentration and cognitive resources than an active, response-based task such as the IAT. In fact, Coates and Campbell [48] noticed that the IAT created such an extensive processing load that even obtrusive distractors during the test did not have an effect on attending the task. Further, the stimuli of the ‘food’ and ‘non-food item’ categories used in the IAT test of the current study were by design extremely similar. This increased difficulty of discrimination has been connected with increased attentional capture as well as decreased task performance compared to tasks with easier stimulus discrimination.

![Figure 5](image-url)  

**Fig. 5.** Non-parametrical Spearman correlations between IAT effects (x-axis) and ERP amplitudes (y-axis) in fasted (top row) and fed (bottom row) states. Significant correlations (p < .05) were found for the central-parietal N400 in the fasted state, and for the parietal N400 and LPP components in the fed state.
As the fasted state reduces cognitive resources, these observations are in line with the work mentioned above relating to task discrimination difficulty [50,51,56]. As the parietal P3 weakens with increasing task difficulty, and fasting might make cognitive tasks even harder to execute as well as influence the P3 component, these two phenomena might exert a cumulative effect on the P3 (and possibly the LPP, which is known to share many qualities of the P3). Therefore, in a task including difficult discrimination between stimuli, it might be hard to determine their task-relevance or motivational value.

In addition, learning may have further affected the task difficulty between fasted and fed states in this study. All participants completed the IAT test first in a fasted state and then postprandially. This means that a learning effect was present despite the use of practice blocks and the postprandial task might have been easier to perform due to the participants being more familiar with the task. Therefore, this change in subjective competence may have added to the change seen in ERP amplitudes and contributed to the faster reaction times in the postprandial IAT [53].

The study group considered the possibility of a learning or familiarity effect when designing the study, but also considered the benefits of running both IAT sessions during a single study visit of each participant. Compared to measurements performed during two separate days, with a fasting period in between, using the current design the variability in the state of the participants (e.g. psychological and physiological) was minimized. This also enabled the use of the same EEG setup in both sessions, which eliminates cross-measurement variability, due to e.g. EEG impedance optimization and cap positioning, in the biosignals. All this amounted to better replicability of the measurements. As a drawback of this design, it fixed the fasted state with the first IAT session, making it difficult to separate learning effects from the effects of fasting. Practice blocks were used to minimize the learning effect, but the possibility of this effect cannot be ruled out completely.

Taking together, in this study, due to the difficulty of discrimination and high level of attentional capture of the IAT used in this study, motivation-related ERPs (P3, LPP) might have been influenced by hedonic motivation and simultaneously also strongly modulated by the task-related motivation towards the stimuli. Therefore, while fasting increased the hedonic value of the food stimuli as indicated in the IAT effect, this effect was not reflected in ERPs in which such effects were subsumed by the effects of the relatively demanding task. The ERP amplitudes were predominantly affected by the challenges raised by this IAT task with difficult stimulus discrimination, and the difficulty was even stronger in the fasted state, causing the processing of the categorization events to be harder compared to the fed state.

Finally, there is a possibility that the ERP findings are influenced by each other. Additional statistical analyses indicated that N400 differences by metabolic state were independent of the P3. However, as other relative changes in temporally adjacent ERP amplitudes were not significant, it is possible that a preceding component (for example, the N400 preceding the LPP) contributed to the changes observed in the following component (for example, changes in the LPP). It is also possible, that an underlying larger wave could have influenced the component differences seen in this study. Future research could attempt to clarify this possible connection.

An intriguing question for future research is whether the hedonic and cognitive bases for implicit attitudes share a neural background seen in the P3 and LPP in this study. Another explanation would be that they originate from different neural locations, which merely manifest in the same timeframe and in the parietal area.

5. Conclusions

In summary, event-related potentials were observed to reflect the IAT effect in a food-related context. The N400, P3 and LPP components are evoked in a food-related IAT test in a similar way to IATs used in other contexts. Additionally, the individual N400 and LPP deflections correlated strongly with the individual IAT effect, further suggesting that the food-related IAT effect reflects implicit food bias detected in neural deflections. Furthermore, fasting increases implicit hedonic motivation towards food, but also simultaneously likely reduces cognitive resources. This likely makes the determination of the value of novel, task-relevant stimuli harder, whereas postprandially and with practice this determination becomes easier.

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Declarations of interest

None.

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