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Article

# Obesity and Insulin Resistance Moderate Neural Responses to the Affective Processing of Unpleasant, But Not Pleasant, Stimuli

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## Abstract

**Background/Objectives:** Obesity and insulin resistance (IR) increase the risk for mood disorders and may impair emotional experiences. This study investigated whether obesity and/or IR moderated the links between brain potentials and affective processing during young adulthood. **Methods:** Thirty young adults completed a passive picture-viewing task utilizing the International Affective Picture System while real-time electroencephalography was simultaneously recorded. Two event-related potential components—early posterior negativity (EPN) and late positive potential (LPP)—were quantified. Affective processing parameters included the mean valence ratings and stimulus-to-response-onset reaction times in response to unpleasant, pleasant, and neutral images. Body fat percentage and Homeostatic Model Assessment for Insulin Resistance values were measured. Hierarchical moderated regression analysis was utilized to test the interrelationships between brain potentials, adiposity, IR, and affective processing parameters. **Results:** In the Negative–Neutral valence condition, lean and insulin-sensitive participants gave less negative valence ratings to unpleasant versus neutral images when late-window LPP amplitudes were larger, whereas respective counterparts showed no such relationship. Contrariwise, obesity and IR did not moderate the links between LPP amplitudes and affective processing parameters in the Positive–Neutral or Negative–Positive conditions. Additionally, EPN amplitudes and affective processing scores were not moderated by obesity or IR across any of the valence conditions. **Conclusions:** Lean and insulin-sensitive young adults showed attenuated negative affective processing of unpleasant versus neutral stimuli through increased brain activity, whereas obese and insulin-resistant young adults did not. In contrast, obesity and IR did not modify the relationship between neural activity and positive affective processing in young adults.

**Keywords:** affective processing; early posterior negativity (EPN); electroencephalography (EEG); emotion; event-related potentials (ERPs); insulin resistance; late positive potential (LPP); neurophysiology; obesity

## 1. Introduction

Obesity increases the risk for mood disorders [1,2] and alterations in emotional processing [3,4]. Generally, obesity has been associated with enhanced automatic negative affective processing (i.e., more difficulties in suppressing the automatic processing of information associated with negative emotions) [3,5,6] and attenuated automatic positive affective processing (i.e., diminished automatic processing of information associated with positive emotions) [4]. However, there is a notable dearth of evidence that has investigated the underlying mechanisms of how obesity may alter neural activity and underlying affective processing, particularly for positive affect. Considering that ever-increasing global adult obesity rates have now reached 16% [7], further investigation is crucial to clarify these mechanisms. One such mechanism could be obesity-induced insulin resistance (IR). Insulin, a pancreatic hormone, functions in whole-body glycolytic processes [8]. IR emerges when target tissues are less responsive to insulin stimulation [9]. Like adiposity, IR also increases the risk for mood disorders [10,11] and emotional processing modifications [12]. Yet there remains a substantial paucity of studies that have investigated how obesity and especially IR influence affective processing.

Obesity and IR may impair affective processing by inducing brain structural and functional alterations in structures that function in emotion regulation. For example, greater adiposity has been linked to fewer dopamine striatal D2 receptors [13], which may explain why blunted positive affective processing has been found in these subjects [4]. Furthermore, a reduction in dopamine striatal D2 receptors has been linked to impaired prefrontal metabolism within the orbitofrontal and anterior cingulate cortices in those with obesity [14]. Considering the neuroanatomical overlap of these structures with the dorsolateral and ventrolateral prefrontal cortices that modulate emotional reactivity [15], these obesity-related neural modifications may reduce prefrontal cortical modulation of emotional reactivity in response to affective input from the amygdala, resulting in enhanced negative affective processing and amplified responses to unpleasant stimuli. In addition, obesity fosters functional alterations in the amygdala. A neuroimaging study observed blunted activity in the amygdalae of subjects with obesity relative to lean counterparts, which was, in turn, linked to a greater susceptibility to feelings of negative affectivity, particularly fear [16]. IR has also been linked to brain structural and functional alterations. Peripheral IR impedes central signaling, causing central IR [17] and hindering brain glucose metabolism. Chronic central IR engenders progressive brain atrophy [18]. IR-induced atrophy is most pronounced in brain structures that function in affective processing and regulation (e.g., medial temporal lobe, parietal gyri [19]), which may, in turn, contribute to the hampering of emotional processing function over time. Taken together, these findings suggest that impairments in affective processing among those with obesity and/or IR may stem from diminished top-down modulation of affectivity due to obesity- and/or IR-linked alterations in brain structures that function in affective processing.

Empirical evidence has most frequently utilized functional magnetic resonance imaging (fMRI) to investigate how obesity and/or IR influence neural activity and underlying affective processing. Consequently, the underlying electrophysiological mechanisms to elucidate these interrelationships remain underexplored. However, electroencephalography (EEG) may be an adequate alternative neuroimaging approach for investigating such associations, as EEG has superior temporal resolution and is significantly less expensive than fMRI [20,21]. Event-related potentials (ERPs) are defined as voltage fluctuations in the electroencephalogram that are induced by a particular event or stimulus [22]. Each ERP component is functionally differentiated according to: 1) polarity (direction of amplitude deflection); 2) scalp distribution; 3) latency (time and duration of electrocortical activity); and 4) sensitivity to particular task-linked manipulations [23].

Two ERP components—early posterior negativity (EPN) and late positive potential (LPP)—index affective processing [24]. EPN is a negative, occipitotemporal potential with an electrocortical activity trough approximately 200–300 milliseconds (ms) post-stimulus exposure. Larger (i.e., more negative) EPN voltage amplitudes indicate elevated visual attention to emotional versus neutral

stimuli [25] and is particularly sensitive to positive stimuli [26]. LPP is a positive, centroparietal potential that commences 300–400 ms post-stimulus exposure [27,28]. During picture viewing tasks, LPP consistently shows higher (i.e., more positive) amplitude deflections in response to affective versus neutral images [29,30]. As LPP amplitudes are sustained throughout the continuance of image presentation [27], the LPP component is generally segmented into three distinctive latency windows to reflect the functional relevance of neural activity during three sequential affective processing stages: 1) automatic emotional response; 2) sustained attention to and ongoing evaluation of emotional stimuli; and 3) prolonged affective processing, affect regulation (when applicable), and possibly memory encoding [24,31–36]. During passive picture-viewing tasks, LPP amplitudes during the early latency window functionally index emotional salience in terms of motivated attention, with amplitudes reflecting the level of arousal elicited by emotional stimuli [31,32,36], while higher LPP amplitudes during the later latency windows reflect more sustained attention towards and increased processing of affective stimuli relative to neutral [32,33,36] and may also be more sensitive to valence-specific differentiation compared to the early-window LPP [37]. As such, individuals with obesity and IR would be expected to have higher late-window LPP amplitudes and enhanced affective processing in response to unpleasant stimuli as well as lower late-window LPP amplitudes and attenuated affective processing in response to pleasant stimuli compared to lean and insulin-sensitive individuals, respectively. Crucially, however, no studies to date have investigated how the relationships between brain potentials and negative or positive affective processing may differ by levels of body fat or IR, warranting investigation.

In order to help fill these gaps, this study was conducted with two primary aims: 1) to investigate whether obesity and/or IR moderated the relationships between brain potentials and underlying negative and positive affective processing in young adults; and 2) to test whether EEG is a sufficient neuroimaging modality to assess these interrelationships. The central hypotheses were: 1) young adults without obesity or IR will show attenuated negative affective processing through lower late-window LPP amplitudes in response to unpleasant stimuli compared to respective counterparts; and 2) young adults without obesity or IR will show enhanced positive affective processing through higher late-window LPP amplitudes in response to pleasant stimuli compared to respective counterparts.

## 2. Materials and Methods

### 2.1. Participants

Thirty young adults who inhabited the Ames, Iowa, USA location were invited to participate. The sample size was chosen in accordance with the results obtained from a power analysis conducted using G\*power 3.1.9.7 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany), from which the a priori power analysis determined that a sample size of 26 participants was required to test for a linear multiple regression, fixed model,  $R^2$  increase, with a large effect size (Cohen's  $f^2 = 0.35$ ),  $\alpha = 0.05$ , power = 0.80, and the total number of predictors = 7 (3 predictors, 4 covariates).

Inclusion criteria were:

1. aged 18–39 years; and
2. overnight fasting capability (no more than 16 consecutive hours).

Exclusion criteria included:

1. cerebrovascular/neurological diseases (e.g., stroke, multiple sclerosis, traumatic brain injury, cerebral hematoma);
2. major cardiovascular events;
3. major psychiatric disorders (e.g., major depressive disorder, generalized anxiety disorder, schizophrenia, autism spectrum disorders, attention deficit hyperactivity disorder, bipolar disorder);
4. recent drug, alcohol, or substance abuse ( $\leq 6$  months);
5. diabetes mellitus I/II;

6. blood pressure  $\geq 21.3/14.7$  kPa ( $\geq 160/110$  mmHg)
  7. fasting blood glucose values of  $< 3.9$  mmol/L ( $< 70$  mg/dL) or  $> 6.9$  mmol/L ( $> 125$  mg/dL);
  8. current use of medications that impact weight, insulin levels, serum biomarkers, or affective processing (e.g., systemic corticosteroids, weight reduction medications, atypical antipsychotics);
  9. have ferrous metal implants or shrapnel around the head/eyes;
  10. currently pregnant; and
  11. currently use nicotine/tobacco products.
- Approval from the Iowa State University Institutional Review Board was obtained.

## 2.2. Study Design and Protocol

To investigate if obesity and/or IR moderated brain potentials and affective processing, a cross-sectional, observational design was utilized. Study visits included an initial screening and two follow-up visits within a one-month timeframe.

### 2.2.1. Initial Screening Visit

Each potential participant had the consent form thoroughly explained, with signatures obtained during the initial screening visit. Subsequently, the medical history of each potential subject was thoroughly queried. Additionally, height and weight were obtained.

### 2.2.2. First Follow-up Visit

During the first follow-up visit, height and weight were reobtained, and each participant's body fat percentage (BF%) was measured by a dual-energy X-ray absorptiometry scan (DEXA/DXA; Hologic Discovery v.12.3, Hologic, Inc., Marlborough, Massachusetts, USA). Fasting blood serum was collected, from which fasting glucose and insulin values were quantified. Utilizing these values, IR was gauged for each participant in accordance with the Homeostatic Model Assessment for Insulin Resistance (HOMA-IR) formula:  $(\text{fasting glucose (mmol/L)} * \text{fasting insulin (pmol/L)}) / 22.5$  ( $[\text{glucose (mg/dL)} * \text{insulin } (\mu\text{IU/mL})] / 405$ ) [38]. Physical activity levels were self-reported as part of the body composition analysis and categorized as: 1) sedentary (no engagement in physical activity beyond basic movements from daily life); 2) low active ( $< 150$  (moderate) or  $< 75$  (vigorous) minutes of activity weekly); 3) active ( $150$ – $300$  (moderate) or  $75$ – $150$  (vigorous) minutes of activity per week); and 4) very active ( $> 300$  (moderate) or  $> 150$  (vigorous) minutes of weekly activity [39]). Participants were subsequently dichotomized via whether physical activity levels totaled  $< 150$  (moderate) or  $< 75$  (vigorous) minutes weekly (sedentary/low active) versus  $\geq 150$  (moderate) or  $\geq 75$  (vigorous) minutes weekly (active/very active), as done previously [40].

### 2.2.3. Second Follow-up Visit

Subjects completed the International Affective Picture System (IAPS) task [41] while brain activity was concomitantly recorded via EEG during the second follow-up visit. Participants were singly shown 64 randomized neutral ( $n=21$ ), unpleasant ( $n=22$ ), and pleasant ( $n=21$ ) images for two seconds each, then instructed to rate the magnitude of pleasantness or unpleasantness of each image (i.e., valence ratings), where 1="very positive," 2="somewhat positive," 3="somewhat negative," and 4="very negative." Unpleasant and pleasant images were matched for normative arousal ratings in order to ensure that differences in neural responses were attributable to valence rather than arousal. The task photo identification numbers used in this study are listed in **Table A1**. IAPS task parameters were scored in E-Prime\*3 [42]. Affective processing parameters included the mean valence ratings (an indicator of the magnitude of negativity or positivity felt in response to unpleasant or pleasant stimuli, respectively [43]) of and stimulus-to-response-onset reaction times (RTs, which reflect affective processing and attentional engagement [44] and are sensitive to valence-specific differentiation [45]) to unpleasant, pleasant, and neutral images.

Subsequently, affective processing scores were contrasted for each valence condition as follows:

1. Negative minus Neutral;
2. Positive minus Neutral; and
3. Negative minus Positive.

However, because valence ratings reflect opposite degrees of unpleasantness or pleasantness for emotionally-valenced pictures, the calculation for the mean valence rating scores in the oppositely-valenced contrasted condition (i.e., Negative minus Positive) was accordingly adjusted as: Negative minus (4 – Positive).

### 2.3. Electroencephalography

As described previously [40], EEG was recorded using an electrode array cap comprised of 64 Ag/AgCl electrodes (Sands Research, El Paso, Texas, USA), in alignment with the standards defined by the 10-10 International System of electrode placement, and was interfaced to a digital bio-potential amplifier (DBPA-1; Sensorium Inc., Charlotte, Vermont, USA). A sampling rate of 2,048 Hz was used. Utilizing EEGLab (Version 2021.1 [46]) in MatLab (Version R2022a, MathWorks, Inc., Natick, Massachusetts, USA), the EEG preprocessing procedure included:

1. the application of a high-pass ( $\leq 0.1$  Hz) filter followed by a low-pass ( $\geq 30$  Hz) filter (using gain 1,000, 16-bit A/D conversion);
2. continuous EEG data was epoched into two-second segments post-stimulus onset (0–2.0 second latency window);
3. standardized the whole-brain amplitude values via average reference computation;
4. eliminated noisy channels through an automatic epoch rejection method (channel fluctuations  $\geq 1,000$   $\mu$ V);
5. computed an Independent Component Analysis (ICA) using the Multiple Artifact Rejection Algorithm (MARA) toolbox [47,48];
6. eliminated artifacts using a peer-reviewed algorithm and statistical parameters [49]; and
7. exported the whole time-course grand means for each valence condition to a .csv file.

### 2.4. Event-Related Potential Components

Grand-mean averaged waveforms were utilized to quantify the EPN and LPP components as follows:

1. EPN: six occipitotemporal electrodes (O1/2, PO7/8, P7/8; [50,51]) between 200–280 ms post-stimulus exposure [52,53]; and
2. LPP: ten centroparietal electrodes (CPz, CP1/2, CP3/4, Pz, P1/2, P3/4; [54,55]) across three latency windows, defined as the early (400–800 ms), middle (800–1,200 ms), and late (1,200–2,000 ms) windows [56,57].

EPN and LPP amplitudes from each valence condition were then contrasted as:

1. Negative–Neutral;
2. Positive–Neutral; and
3. Negative–Positive.

### 2.5. Statistical Analysis

Participants were stratified into two separate groups based on BF% (lean ( $n=8$ ) versus obese ( $n=22$ )) and HOMA-IR (insulin-sensitive ( $n=18$ ) versus insulin-resistant ( $n=12$ )) values to assess between-group differences. Lean versus obese were respectively defined as a BF% of  $<25\%$  (males) and  $<35\%$  (females) versus  $\geq 25\%$  (males) and  $\geq 35\%$  (females) [58]. As previously recommended [59,60], HOMA-IR values of  $<2.0$  versus  $\geq 2.0$  defined insulin sensitivity versus IR, respectively. Statistical comparisons of participant characteristics were conducted using chi-square, Fisher's exact, or independent-samples t-tests in SPSS Statistics (Version 31.0.0.0; IBM Corp., Armonk, New York, USA). Significance was set at  $p \leq 0.05$  for group comparisons.

Hierarchical moderated regression analyses tested whether obesity and/or IR moderated the relationships between brain potentials and affective processing utilizing the PROCESS macro for SPSS (Version 4.2 [61]). All continuous variables were mean-centered prior to analysis to eliminate multicollinearity issues. A multiple imputations procedure in SPSS was applied to impute missing affective processing parameters ( $n=2$ ). The first step of each moderation model tested whether the predictor and moderator variables independently accounted for a significant proportion of the variance for the outcome variable. For each contrasted valence condition, the first step included a predictor (EPN, LPP voltage amplitudes), a moderator (BF%, HOMA-IR), an outcome variable (valence ratings, RTs), and all significant ( $p \leq 0.10$ ) covariates (age, physical activity levels, race/ethnicity, sex). In the second step, each moderation model was retested after the addition of the interaction term (predictor\*moderator), with all covariates readded. In both steps, each non-significant covariate was singly eliminated from each model in descending order of significance. The Bonferroni correction was applied to correct for multiple comparison of associations, in which  $p \leq 0.0063$  was considered statistically significant.

### 3. Results

#### 3.1. Participant Characteristics

As delineated in **Table 1**, demographic and clinical characteristics were compared between stratified adiposity (lean versus obese) and IR (insulin-sensitive versus insulin-resistant) groups. In summary, subjects with obesity and IR had more insulin dysregulation compared to respective counterparts. Additionally, subjects with obesity showed greater glucose dysregulation. Finally, subjects with IR participated in less weekly physical activity and had higher BF%s and diastolic blood pressure.

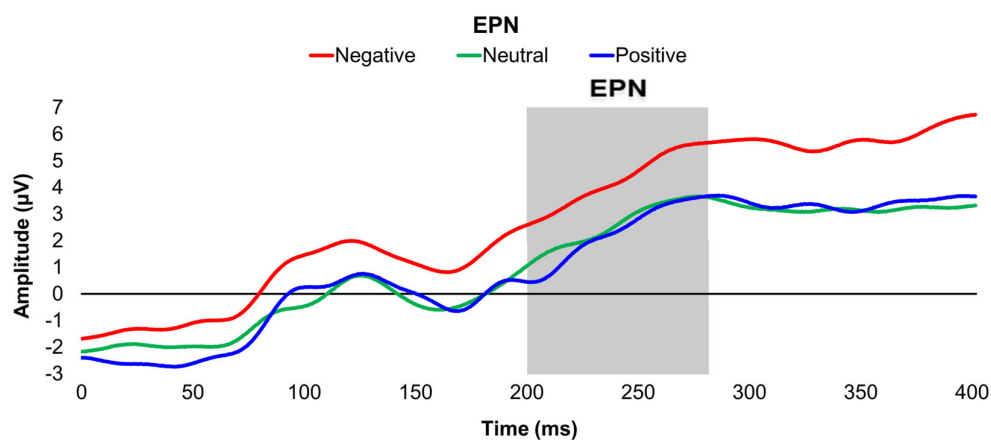
**Table 1.** Participant characteristic comparisons by adiposity and insulin groups.

| Data (unit)                      | Adiposity    |                   |                    |                    | Insulin                  |                          |                    |
|----------------------------------|--------------|-------------------|--------------------|--------------------|--------------------------|--------------------------|--------------------|
|                                  | Total (n=30) | Lean (n=8)        | Obese (n=22)       | t value/Chi-square | Insulin-sensitive (n=18) | Insulin-resistant (n=12) | t value/Chi-square |
| Age (years)                      | 25.7 (5.3)   | 23.3 (4.1)        | 26.5 (5.5)         | $t = -1.54$        | 24.9 (5.6)               | 26.8 (4.9)               | $t = -0.98$        |
| Sex (n females (%))              | 15 (50.0%)   | 3 (37.5%)         | 12 (54.5%)         | $\chi^2 = 0.68$    | 8 (44.4%)                | 7 (58.3%)                | $\chi^2 = 0.56$    |
| <b>Activity Level (n (%))</b>    |              |                   |                    | $\chi^2 = 4.18$    |                          |                          | $\chi^2 = 5.63^*$  |
| <i>Sedentary/Low Active</i>      | 20 (66.7%)   | 3 (37.5%)         | 17 (77.3%)         |                    | <b>9 (50.0%)</b>         | <b>11 (91.7%)</b>        |                    |
| <i>Active/Very Active</i>        | 10 (33.3%)   | 5 (62.5%)         | 5 (22.7%)          |                    | <b>9 (50.0%)</b>         | <b>1 (8.3%)</b>          |                    |
| Race/Ethnicity (n (%))           |              |                   |                    | $\chi^2 = 3.62$    |                          |                          | $\chi^2 = 5.17$    |
| White                            | 24 (80.0%)   | 5 (62.5%)         | 19 (86.4%)         |                    | 13 (72.2%)               | 11 (91.7%)               |                    |
| Asian                            | 5 (16.7%)    | 3 (37.5%)         | 2 (9.1%)           |                    | 5 (27.8%)                | 0 (0.0%)                 |                    |
| Hispanic/Latinx                  | 1 (3.3%)     | 0 (0.0%)          | 1 (4.5%)           |                    | 0 (0.0%)                 | 1 (8.3%)                 |                    |
| Black                            | 0 (0.0%)     | 0 (0.0%)          | 0 (0.0%)           |                    | 0 (0.0%)                 | 0 (0.0%)                 |                    |
| <b>BF% (DEXA)</b>                | 37.1 (10.3)  | <b>24.8 (4.7)</b> | <b>41.6 (7.9)</b>  | $t = -5.64^{***}$  | <b>31.6 (8.5)</b>        | <b>45.5 (6.7)</b>        | $t = -4.76^{***}$  |
| <b>BMI</b>                       | 29.3 (8.2)   | <b>21.0 (1.6)</b> | <b>32.2 (7.5)</b>  | $t = -6.94^{***}$  | <b>24.5 (5.3)</b>        | <b>36.4 (6.4)</b>        | $t = -5.74^{***}$  |
| <b>BP, diastolic (kPa)</b>       | 10.2 (1.7)   | 9.6 (2.0)         | 10.5 (1.5)         | $t = -1.26$        | <b>9.7 (1.6)</b>         | <b>11.1 (1.4)</b>        | $t = -2.33^*$      |
| BP, systolic (kPa)               | 16.2 (2.1)   | 16.6 (2.8)        | 16.0 (1.7)         | $t = 0.68$         | 16.0 (2.4)               | 16.6 (1.3)               | $t = -0.75$        |
| <b>Glucose (mmol/L), fasting</b> | 5.0 (0.5)    | <b>4.7 (0.4)</b>  | <b>5.1 (0.4)</b>   | $t = -2.38^*$      | 4.9 (0.5)                | 5.2 (0.5)                | $t = -1.50$        |
| Height (meters)                  | 1.7 (0.1)    | 1.8 (0.1)         | 1.7 (0.1)          | $t = 0.43$         | 1.7 (0.1)                | 1.7 (0.1)                | $t = -0.37$        |
| Hemoglobin A1c (%)               | 5.4 (0.2)    | 5.3 (0.1)         | 5.4 (0.2)          | $t = -1.05$        | 5.3 (0.2)                | 5.4 (0.2)                | $t = -1.36$        |
| <b>HOMA-IR</b>                   | 2.6 (2.5)    | <b>0.9 (0.3)</b>  | <b>3.3 (2.7)</b>   | $t = -4.24^{***}$  | <b>1.2 (0.4)</b>         | <b>4.9 (2.8)</b>         | $t = -8.07^{***}$  |
| <b>Insulin (pmol/L), fasting</b> | 69.3 (63.0)  | <b>25.2 (8.5)</b> | <b>85.4 (66.7)</b> | $t = -4.14^{***}$  | <b>31.8 (9.5)</b>        | <b>125.7 (67.5)</b>      | $t = -4.78^{***}$  |

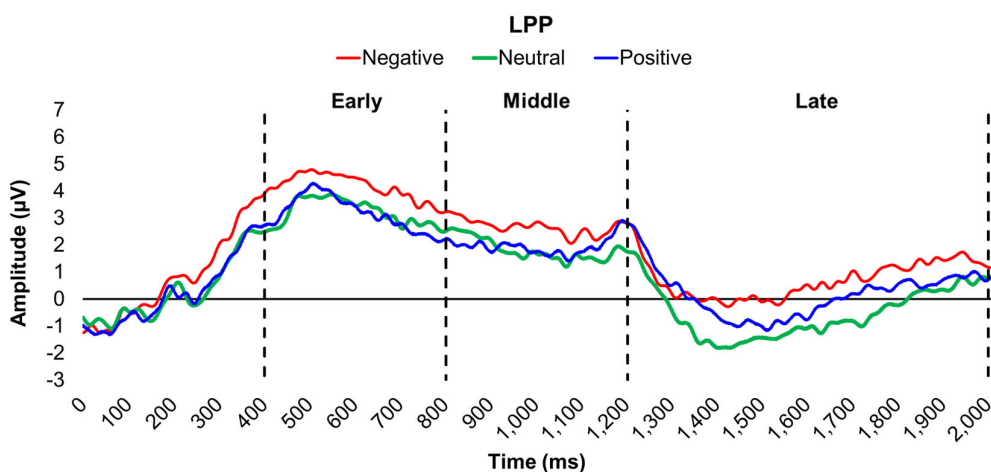
Values are Mean (Standard Deviation) unless otherwise indicated. BF% = body fat percentage; BMI = body mass index; BP=Blood pressure; DEXA = dual-energy X-ray absorptiometry; hemoglobin A1c = glycated hemoglobin; HOMA-IR = homeostatic model assessment for insulin resistance. \* and \*\*\* =  $p$ 's  $\leq 0.05$  and  $\leq 0.005$ , respectively. For the stratified adiposity groups, t-values, chi-square, and Fisher's exact values reflect differences between participants with and without obesity based on a body fat percentage of  $\geq 25\%$  (males) and  $\geq 35\%$  (females) versus  $< 25\%$  (males) and  $< 35\%$  (females), respectively. For the stratified insulin groups, t-values, chi-square, and Fisher's exact values reflect differences between participants with insulin resistance and insulin sensitivity based on HOMA-IR values of  $\geq 2.0$  versus  $< 2.0$ , respectively.

### 3.2. Event-Related Potentials

EPN and LPP grand-mean averaged waveforms across the sample are illustrated for each valence condition in **Figures 1a–b**. For EPN (**Figure 1b**), positively-valenced images elicited the largest (i.e., most negative) amplitudes, while negatively-valenced images evoked the smallest. For LPP (**Figure 1b**), negatively-valenced pictures generated the largest (i.e., most positive) amplitudes across all latency windows, while positively-valenced pictures evoked the smallest during the early latency window and neutrally-valenced pictures evoked the smallest during the later latency windows.



(a)



(b)

**Figure 1.** Line graphs depict the grand-mean averaged EPN (a) and LPP (b) waveforms across all participants after viewing negatively- (red), neutrally- (green), and positively-valenced (blue) pictures during an International Affective Picture System task. Amplitude was measured in microvolts ( $\mu\text{V}$ ); time was measured in milliseconds. EPN = early posterior negativity; LPP = late positive potential; ms = milliseconds. Early, middle, and late latency windows of the LPP component = 400–800 ms, 800–1,200 ms, and 1,200–2,000 ms post-stimulus onset, respectively.

### 3.3. Neural Amplitudes by Categorical Groups

**Table 2** presents the comparisons of the differenced grand-mean averaged EPN and LPP waveforms in each contrasted picture condition (i.e., Negative minus Neutral, Positive minus Neutral, and Negative minus Positive) by stratified adiposity (also see **Figures 2a–f** (differenced waveforms) and **Supplementary Figure S1a–f** (non-differenced waveforms for each separate valence condition)) and IR levels (also see **Figures 3a–f** (differenced waveforms) and **Supplementary Figure S2a–f** (non-differenced waveforms for each separate valence condition)). Concisely, participants without obesity or IR elicited higher LPP amplitudes during the late latency window in response to unpleasant versus neutral pictures than did lean or insulin-sensitive counterparts, respectively (see **Figures 2b/Supplementary Figure 1b** and **3b/Supplementary Figure 2b**). Furthermore, participants with obesity evoked larger LPP amplitudes during the early latency window in the contrasted Negative–Positive valence condition (see **Figure 2f/Supplementary Figure 1f**).

### 3.4. Affective Processing Parameters by Categorical Groups

Differences in affective processing parameters were assessed by stratified adiposity and IR groups for each contrasted valence condition (see Table 3). In summary, participants with IR had slower RTs in response to unpleasant versus neutral images in comparison to insulin-sensitive subjects. Additionally, participants with obesity gave overall higher (i.e., more negative) valence ratings to emotional pictures in the contrasted Negative–Positive valence condition.

### 3.5. Neural Amplitudes and Affective Processing

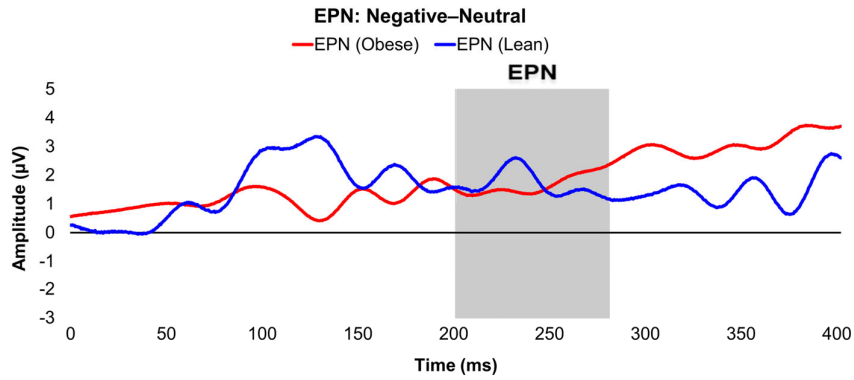
Table 4 displays the correlation matrix between the ERPs and affective processing parameters in each contrasted condition. Succinctly, EPN amplitudes negatively correlated with RTs in the Negative–Positive condition, where greater amplitudes were linked to more negative valence ratings of unpleasant pictures relative to pleasant.

Notably, across all contrasted valence conditions, LPP amplitudes during the late latency window were consistently inversely associated with mean valence ratings, suggesting that higher late-window LPP amplitudes were correlated with less overall negative (for the Negative–Neutral and Negative–Positive conditions) and more overall positive (for the Positive–Neutral condition) valence ratings; however, none of these inverse associations reached statistical significance.

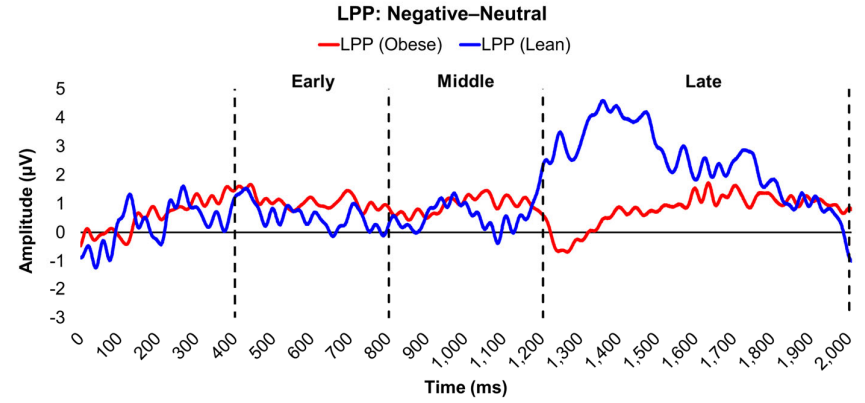
**Table 2.** Comparisons of event-related potentials by adiposity and insulin groups.

| ERP Components           | Adiposity  |                  |                  |                         | Insulin           |                   |                        |
|--------------------------|------------|------------------|------------------|-------------------------|-------------------|-------------------|------------------------|
|                          | Total      | Lean             | Obese            | t value                 | Insulin-sensitive | Insulin-resistant | t value                |
| <b>Negative–Neutral</b>  |            |                  |                  |                         |                   |                   |                        |
| <i>EPN</i>               | 1.7 (2.7)  | 1.7 (3.0)        | 1.6 (2.6)        | <i>t</i> = 0.04         | 1.1 (2.6)         | 2.5 (2.6)         | <i>t</i> = -1.37       |
| <i>Early LPP</i>         | 0.9 (1.9)  | 0.6 (2.5)        | 1.1 (1.7)        | <i>t</i> = -0.64        | 0.8 (2.1)         | 1.2 (1.7)         | <i>t</i> = -0.47       |
| <i>Middle LPP</i>        | 0.8 (2.2)  | 0.6 (2.2)        | 0.9 (2.2)        | <i>t</i> = -0.38        | 0.7 (2.1)         | 1.1 (2.4)         | <i>t</i> = -0.45       |
| <i>Late LPP</i>          | 1.2 (1.8)  | <b>2.4 (2.3)</b> | <b>0.8 (1.5)</b> | <b><i>t</i>= 2.31*</b>  | <b>1.8 (1.9)</b>  | <b>0.3 (1.3)</b>  | <b><i>t</i>= 2.37*</b> |
| <b>Positive–Neutral</b>  |            |                  |                  |                         |                   |                   |                        |
| <i>EPN</i>               | -0.3 (2.6) | -0.7 (2.1)       | -0.2 (2.8)       | <i>t</i> = -0.49        | -0.8 (2.5)        | 0.4 (2.6)         | <i>t</i> = -1.22       |
| <i>Early LPP</i>         | -0.1 (2.3) | 0.6 (1.7)        | -0.3 (2.5)       | <i>t</i> = 0.96         | 0.0 (2.3)         | -0.2 (2.5)        | <i>t</i> = 0.26        |
| <i>Middle LPP</i>        | 0.1 (2.7)  | 0.3 (2.0)        | 0.1 (2.9)        | <i>t</i> = 0.17         | 0.2 (2.5)         | 0.0 (3.1)         | <i>t</i> = 0.13        |
| <i>Late LPP</i>          | 0.7 (2.2)  | 1.9 (2.1)        | 0.3 (2.2)        | <i>t</i> = 1.87         | 1.2 (1.9)         | -0.1 (2.6)        | <i>t</i> = 1.69        |
| <b>Negative–Positive</b> |            |                  |                  |                         |                   |                   |                        |
| <i>EPN</i>               | 2.0 (2.7)  | 2.4 (3.1)        | 1.8 (2.6)        | <i>t</i> = 0.50         | 1.9 (2.9)         | 2.1 (2.5)         | <i>t</i> = -0.18       |
| <i>Early LPP</i>         | 1.0 (1.6)  | <b>0.0 (1.6)</b> | <b>1.4 (1.4)</b> | <b><i>t</i>= -2.38*</b> | 0.8 (1.7)         | 1.3 (1.4)         | <i>t</i> = -0.97       |
| <i>Middle LPP</i>        | 0.7 (2.0)  | 0.3 (1.2)        | 0.9 (2.2)        | <i>t</i> = -0.65        | 0.5 (1.9)         | 1.0 (2.2)         | <i>t</i> = -0.68       |
| <i>Late LPP</i>          | 0.5 (2.0)  | 0.5 (2.0)        | 0.5 (2.0)        | <i>t</i> = 0.03         | 0.6 (2.0)         | 0.4 (2.0)         | <i>t</i> = 0.19        |

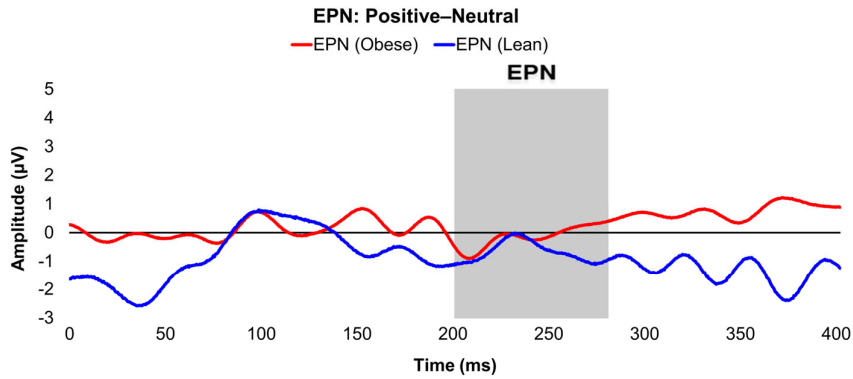
Values are Mean (Standard Deviation) unless otherwise indicated. Amplitude was measured in microvolts ( $\mu\text{V}$ ). EPN = early posterior negativity; ERP = event-related potential; LPP = late positive potential. \* =  $p \leq 0.05$ . In each contrasted valence condition, the mean ERP amplitudes of a neutrally- or oppositely-valenced condition were subtracted from the mean ERP amplitudes of an emotionally-valenced condition (i.e., negative or positive) as follows: 1) Negative–Neutral; 2) Positive–Neutral; and 3) Negative–Positive. Early, middle, and late latency windows of the LPP component = 400–800 ms, 800–1,200 ms, and 1,200–2,000 ms post-stimulus onset, respectively. For the stratified adiposity groups, t-values reflect differences between participants with and without obesity based on a body fat percentage of  $\geq 25\%$  (males) and  $\geq 35\%$  (females) versus  $< 25\%$  (males) and  $< 35\%$  (females), respectively. For the stratified insulin groups, t-values reflect differences between participants with insulin resistance and insulin sensitivity based on HOMA-IR values of  $\geq 2.0$  versus  $< 2.0$ , respectively.



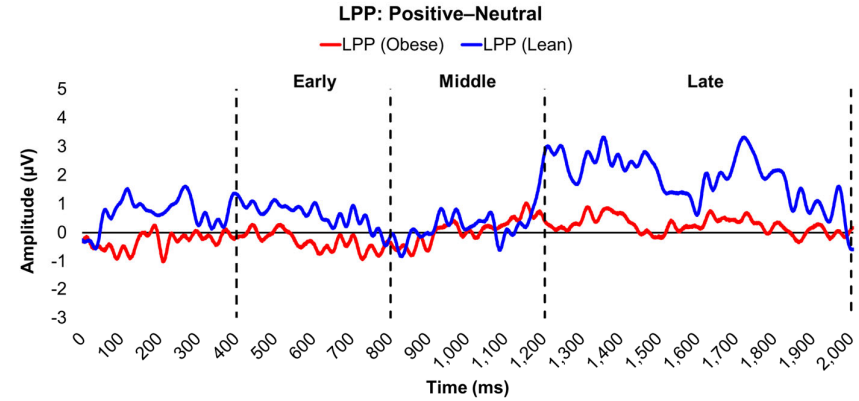
(a)



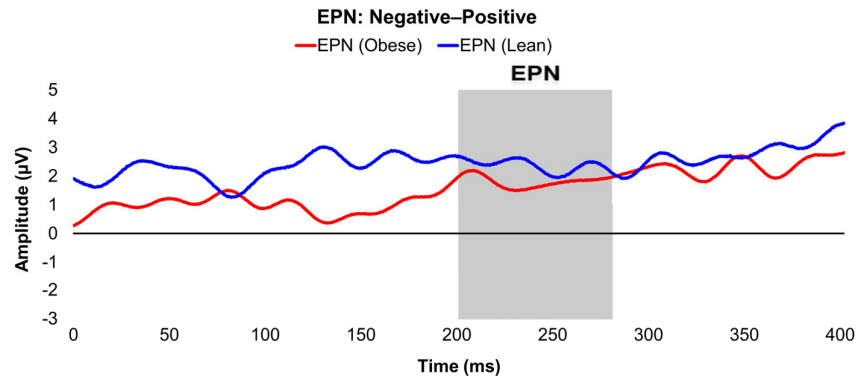
(b)



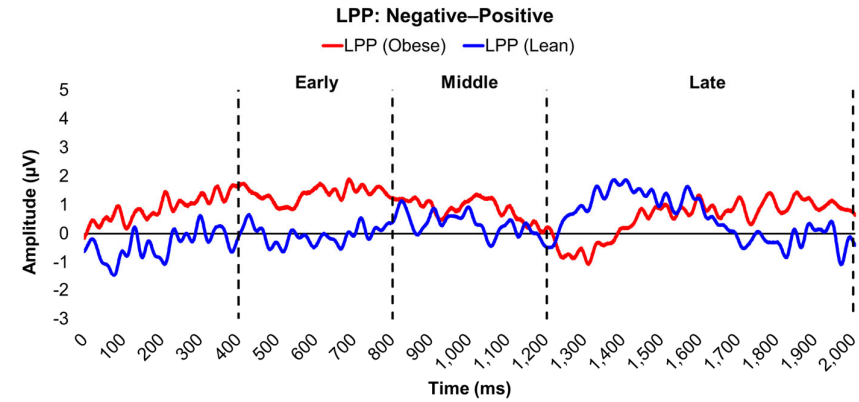
(c)



(d)

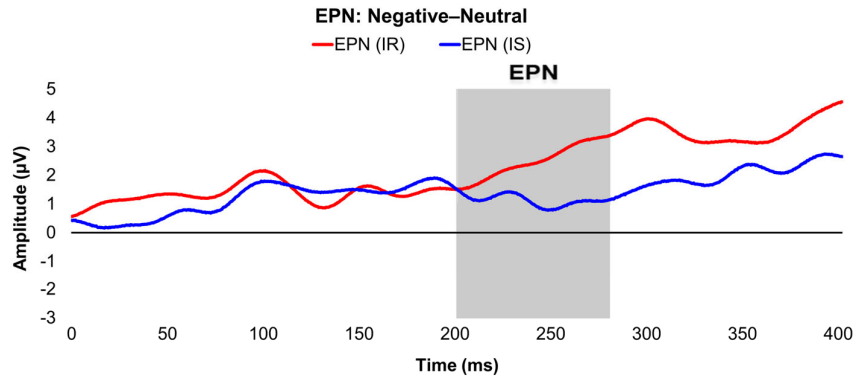


(e)

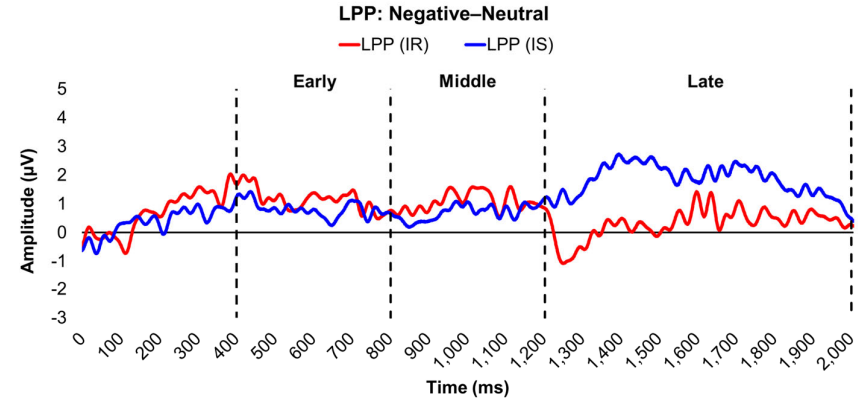


(f)

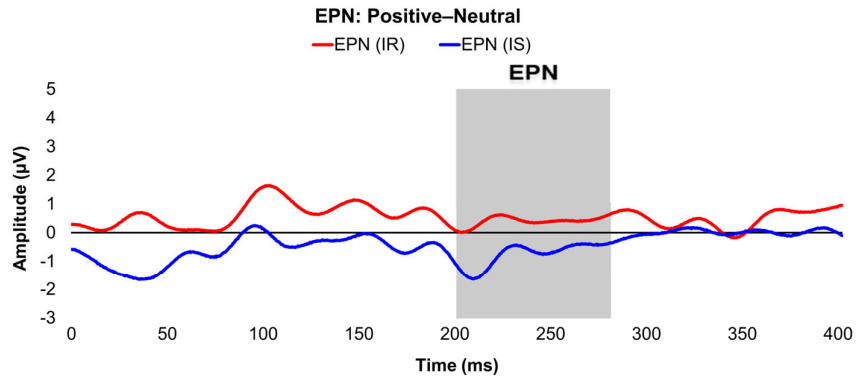
**Figure 2.** Line graphs show the comparisons of the differenced grand-mean averaged EPN (left) and LPP (right) waveforms in the contrasted picture conditions (i.e., Negative minus Neutral (a–b), Positive minus Neutral (c–d), and Negative minus Positive (e–f) EPN and LPP waveforms) between lean (body fat percentage of <25% (males) and <35% (females), in blue) versus obese (body fat percentage of  $\geq 25\%$  (males) and  $\geq 35\%$  (females), in red) subjects. Amplitude was measured in microvolts ( $\mu\text{V}$ ); time was measured in milliseconds. EPN = early posterior negativity; LPP = late positive potential; ms = milliseconds. Early, middle, and late latency windows of the LPP component = 400–800 ms, 800–1,200 ms, and 1,200–2,000 ms post-stimulus onset, respectively.



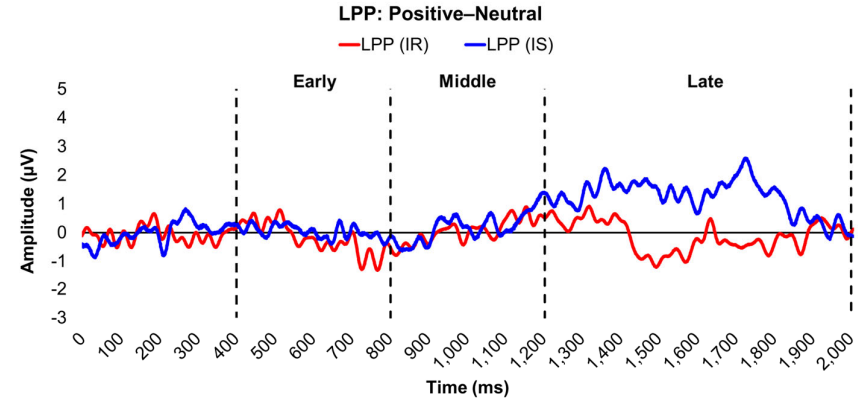
(a)



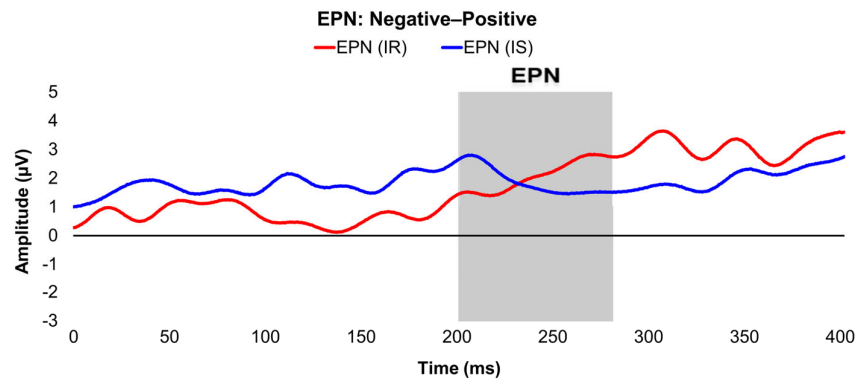
(b)



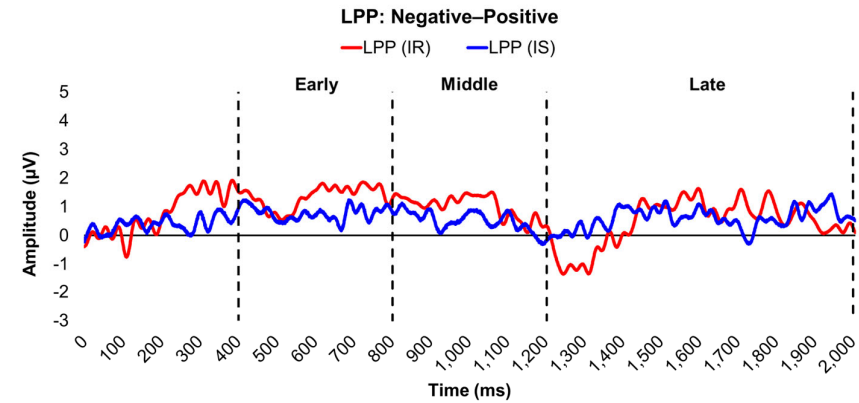
(c)



(d)



(e)



(f)

**Figure 3.** Line graphs show the comparisons of the differenced grand-mean averaged EPN (left) and LPP (right) waveforms in the contrasted picture conditions (i.e., Negative minus Neutral (a–b), Positive minus Neutral (c–d), and Negative minus Positive (e–f) EPN and LPP waveforms) between insulin-sensitive (HOMA-IR values of  $<2.0$ , in blue) versus insulin-resistant (HOMA-IR values of  $\geq 2.0$ , in red) subjects. Amplitude was measured in microvolts ( $\mu\text{V}$ ); time was measured in milliseconds. EPN = early posterior negativity; IR = insulin-resistant; IS = insulin-sensitive; LPP = late positive potential; ms = milliseconds. Early, middle, and late latency windows of the LPP component = 400–800 ms, 800–1,200 ms, and 1,200–2,000 ms post-stimulus onset, respectively.

**Table 3.** Comparisons of affective processing task scores by adiposity and insulin groups.

| Affective Processing Parameters | Total        | Adiposity    |              |             | Insulin              |                     |               |
|---------------------------------|--------------|--------------|--------------|-------------|----------------------|---------------------|---------------|
|                                 |              | Lean         | Obese        | t value     | Insulin-sensitive    | Insulin-resistant   | t value       |
| Rating (Negative–Neutral)       | 1.6 (0.4)    | 1.5 (0.5)    | 1.6 (0.3)    | $t = -0.37$ | 1.6 (0.4)            | 1.5 (0.3)           | $t = 0.57$    |
| RT (Negative–Neutral)           | 2.6 (206.1)  | -1.3 (154.2) | 4.0 (225.2)  | $t = -0.06$ | <b>-59.0 (182.9)</b> | <b>95.0 (211.6)</b> | $t = -2.12^*$ |
| Rating (Positive–Neutral)       | -0.4 (0.2)   | -0.5 (0.2)   | -0.4 (0.2)   | $t = -1.26$ | -0.5 (0.2)           | -0.3 (0.2)          | $t = -0.91$   |
| RT (Positive–Neutral)           | 25.5 (174.4) | 58.9 (213.0) | 13.4 (162.2) | $t = 0.63$  | 7.8 (213.8)          | 52.1 (91.1)         | $t = -0.78$   |

|                                   |               |                  |                  |                   |               |              |                  |
|-----------------------------------|---------------|------------------|------------------|-------------------|---------------|--------------|------------------|
| <i>Rating (Negative–Positive)</i> | 2.7 (0.2)     | <b>2.5 (0.3)</b> | <b>2.7 (0.2)</b> | <i>t</i> = -2.39* | 2.6 (0.2)     | 2.8 (0.2)    | <i>t</i> = -1.64 |
| <i>RT (Negative–Positive)</i>     | -17.8 (216.8) | -30.8 (156.0)    | -13.0 (238.2)    | <i>t</i> = -0.20  | -53.7 (184.3) | 36.2 (257.3) | <i>t</i> = -1.12 |

Values are Mean (Standard Deviation) unless otherwise indicated. Reaction time was measured in milliseconds. RT = reaction time. \* =  $p \leq 0.05$ . In each contrasted valence condition, the affective processing parameters of a neutrally- or oppositely-valenced condition were subtracted from the affective processing parameters of an emotionally-valenced condition (i.e., negative or positive) as follows: 1) Negative–Neutral; 2) Positive–Neutral; and 3) Negative–Positive. For the contrasted oppositely-valenced picture condition, valence ratings were calculated as: Negative–(4–Positive). For the stratified adiposity groups, *t*-values reflect differences between participants with and without obesity based on a body fat percentage of  $\geq 25\%$  (males) and  $\geq 35\%$  (females) versus  $< 25\%$  (males) and  $< 35\%$  (females), respectively. For the stratified insulin groups, *t*-values reflect differences between participants with insulin resistance and insulin sensitivity based on HOMA-IR values of  $\geq 2.0$  versus  $< 2.0$ , respectively.

**Table 4.** Correlation matrix of event-related potentials and affective processing parameters.

| ERP Components           | Negative–Neutral |               | Positive–Neutral |               | Negative–Positive |               |
|--------------------------|------------------|---------------|------------------|---------------|-------------------|---------------|
|                          | Valence Rating   | Reaction Time | Valence Rating   | Reaction Time | Valence Rating    | Reaction Time |
| <b>Negative–Neutral</b>  |                  |               |                  |               |                   |               |
| <i>EPN</i>               | -0.15            | 0.11          | -                | -             | -                 | -             |
| <i>Early LPP</i>         | 0.08             | 0.08          | -                | -             | -                 | -             |
| <i>Middle LPP</i>        | -0.01            | 0.16          | -                | -             | -                 | -             |
| <i>Late LPP</i>          | -0.36            | 0.06          | -                | -             | -                 | -             |
| <b>Positive–Neutral</b>  |                  |               |                  |               |                   |               |
| <i>EPN</i>               | -                | -             | -0.27            | 0.15          | -                 | -             |
| <i>Early LPP</i>         | -                | -             | -0.06            | 0.09          | -                 | -             |
| <i>Middle LPP</i>        | -                | -             | -0.04            | 0.14          | -                 | -             |
| <i>Late LPP</i>          | -                | -             | -0.31            | 0.01          | -                 | -             |
| <b>Negative–Positive</b> |                  |               |                  |               |                   |               |
| <i>EPN</i>               | -                | -             | -                | -             | 0.19              | <b>-0.38*</b> |
| <i>Early LPP</i>         | -                | -             | -                | -             | 0.28              | -0.19         |
| <i>Middle LPP</i>        | -                | -             | -                | -             | 0.31              | -0.08         |
| <i>Late LPP</i>          | -                | -             | -                | -             | -0.08             | -0.15         |

Values show bivariate Pearson correlation coefficients between the independent variables (EPN and LPP amplitude deflections) and the dependent variables (valence ratings, reaction times) for each contrasted condition of the International Affective Picture System task. Amplitude was measured in microvolts ( $\mu\text{V}$ ); reaction time was measured in milliseconds. EPN = early posterior negativity; ERP = event-related potential; LPP = late positive potential. \* =  $p \leq 0.05$ . In each contrasted valence condition, the mean ERP voltage amplitudes and affective processing parameters of a neutrally- or oppositely-valenced condition were subtracted from the mean ERP amplitudes and affective processing parameters of an emotionally-valenced condition (i.e., negative or positive) as follows: 1) Negative–Neutral; 2) Positive–Neutral; and 3) Negative–Positive. For the contrasted oppositely-valenced picture condition, valence ratings were calculated as: Negative–(4–Positive). Early, middle, and late LPP latency windows = 400–800 ms, 800–1,200 ms, and 1,200–2,000 ms post-stimulus onset, respectively.

### 3.6. Moderation Analyses

#### 3.6.1. Negative–Neutral Picture Condition

The results of how BF% and HOMA-IR values moderated the relationships between neural activity and affective processing scores in response to unpleasant versus neutral pictures are shown in **Table 5** for valence ratings and in **Table 6** for RTs. Further slope analyses in **Figures 4a–b** illustrate that, exclusively in participants with low BF% and low-to-medium HOMA-IR values, greater LPP amplitudes during the late latency window were associated with less negative valence ratings in response to unpleasant pictures relative to neutral.

**Table 5.** Hierarchical moderated regression results for Negative vs. Neutral valence ratings

| Variables      | Step 1  |       |       |      |      | Step 2         |                |                |                 |              |
|----------------|---------|-------|-------|------|------|----------------|----------------|----------------|-----------------|--------------|
|                | $\beta$ | $t$   | $R^2$ | $F$  | $p$  | $\beta$        | $t$            | $\Delta R^2$   | $\Delta F$      | $p$          |
| <b>Model 1</b> |         |       | 0.03  | 0.47 | 0.63 |                |                | 0.00           | 0.01            | 0.92         |
| EPN            | -0.15   | -0.79 |       |      |      | -0.15          | -0.78          |                |                 |              |
| BF%            | 0.10    | 0.53  |       |      |      | 0.10           | 0.52           |                |                 |              |
| EPN*BF%        |         |       |       |      |      | 0.02           | 0.10           |                |                 |              |
| <b>Model 2</b> |         |       | 0.02  | 0.33 | 0.73 |                |                | 0.00           | 0.01            | 0.93         |
| EPN            | -0.15   | -0.81 |       |      |      | -0.15          | -0.77          |                |                 |              |
| HOMA-IR        | -0.01   | -0.06 |       |      |      | -0.01          | -0.07          |                |                 |              |
| EPN*HOMA-IR    |         |       |       |      |      | 0.02           | 0.09           |                |                 |              |
| <b>Model 3</b> |         |       | 0.02  | 0.28 | 0.76 |                |                | 0.00           | 0.16            | 0.69         |
| eLPP           | 0.10    | 0.51  |       |      |      | 0.11           | 0.57           |                |                 |              |
| BF%            | 0.12    | 0.62  |       |      |      | 0.13           | 0.67           |                |                 |              |
| eLPP*BF%       |         |       |       |      |      | 0.08           | 0.40           |                |                 |              |
| <b>Model 4</b> |         |       | 0.01  | 0.09 | 0.91 |                |                | 0.01           | 0.13            | 0.73         |
| eLPP           | 0.08    | 0.43  |       |      |      | 0.09           | 0.46           |                |                 |              |
| HOMA-IR        | 0.00    | -0.01 |       |      |      | -0.01          | -0.05          |                |                 |              |
| eLPP*HOMA-IR   |         |       |       |      |      | 0.07           | 0.36           |                |                 |              |
| <b>Model 5</b> |         |       | 0.01  | 0.16 | 0.86 |                |                | 0.05           | 1.28            | 0.27         |
| mLPP           | -0.02   | -0.10 |       |      |      | 0.00           | 0.01           |                |                 |              |
| BF%            | 0.11    | 0.56  |       |      |      | 0.15           | 0.76           |                |                 |              |
| mLPP*BF%       |         |       |       |      |      | 0.22           | 1.13           |                |                 |              |
| <b>Model 6</b> |         |       | 0.00  | 0.00 | 1.00 |                |                | 0.06           | 1.65            | 0.21         |
| mLPP           | -0.01   | -0.06 |       |      |      | -0.04          | -0.21          |                |                 |              |
| HOMA-IR        | 0.01    | 0.03  |       |      |      | -0.09          | -0.42          |                |                 |              |
| mLPP*HOMA-IR   |         |       |       |      |      | 0.26           | 1.29           |                |                 |              |
| <b>Model 7</b> |         |       | 0.13  | 2.06 | 0.15 |                |                | <b>0.25***</b> | <b>10.23***</b> | <b>0.004</b> |
| ILPP           | -0.38   | -1.94 |       |      |      | -0.05          | -0.24          |                |                 |              |
| BF%            | -0.06   | -0.28 |       |      |      | -0.08          | -0.46          |                |                 |              |
| ILPP*BF%       |         |       |       |      |      | <b>0.60***</b> | <b>3.20***</b> |                |                 |              |
| <b>Model 8</b> |         |       | 0.14  | 2.20 | 0.13 |                |                | <b>0.24***</b> | <b>9.89***</b>  | <b>0.004</b> |
| ILPP           | -0.40   | -2.12 |       |      |      | -0.20          | -1.18          |                |                 |              |
| HOMA-IR        | -0.12   | -0.63 |       |      |      | -0.11          | -0.69          |                |                 |              |
| ILPP*HOMA-IR   |         |       |       |      |      | <b>0.52***</b> | <b>3.14***</b> |                |                 |              |

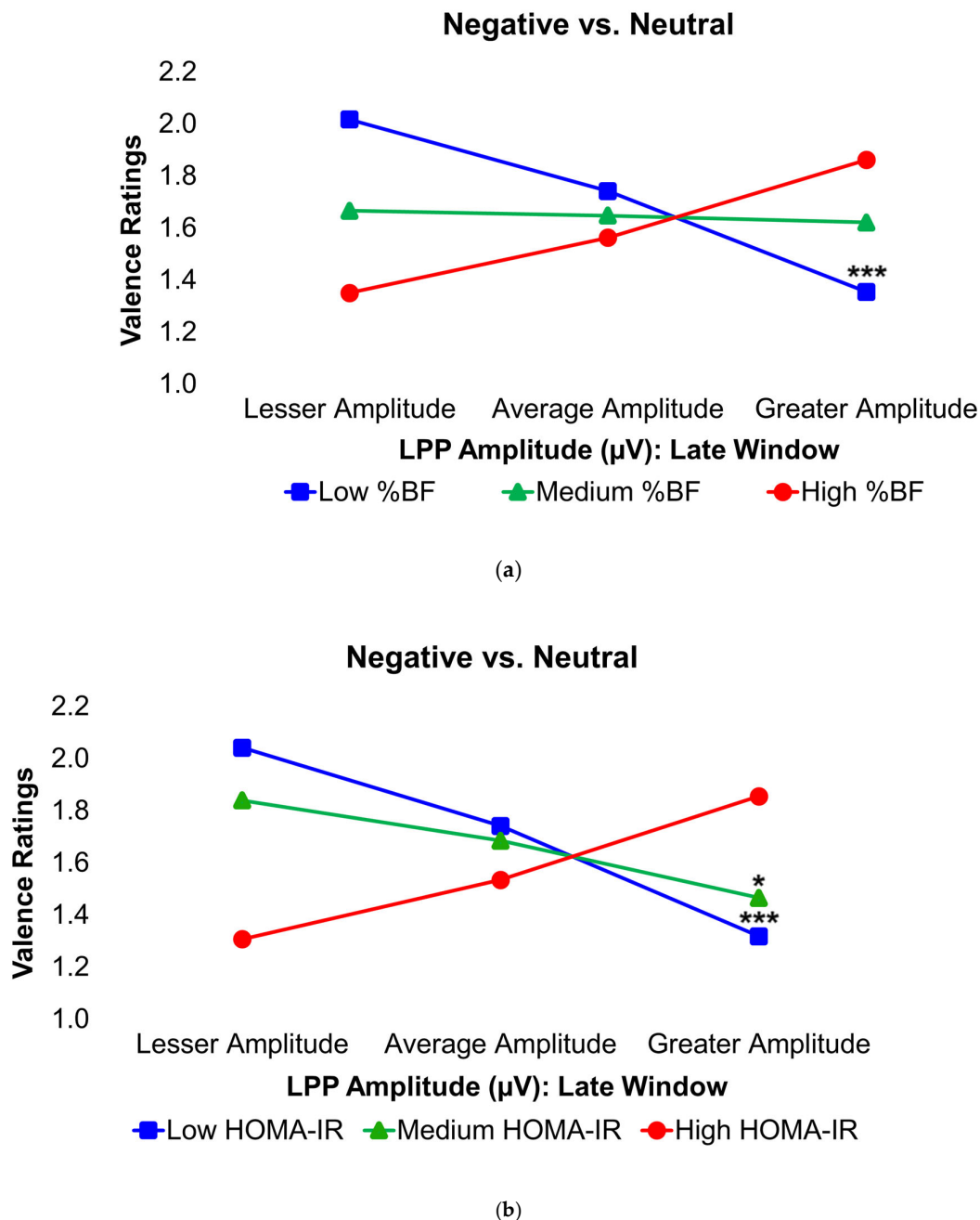
Table displays the results of each step of the hierarchical moderated regression analyses, which tested whether EPN or LPP voltage amplitudes and BF% or HOMA-IR moderated the mean valence ratings after viewing negatively-valenced versus neutrally-valenced pictures. BF% = body fat percentage; eLPP = late positive potential in the early latency window; EPN = early posterior negativity; HOMA-IR = homeostatic model assessment for insulin resistance; ILPP = late positive potential in the late latency window; mLPP = late positive potential in the middle latency window. \*\*\* =  $p \leq 0.005$ .  $\beta$  shows standardized regression coefficients. Only statistically significant covariates ( $p \leq 0.10$ ) were included in each model.

**Table 6.** Hierarchical moderated regression results for Negative vs. Neutral reaction times.

| Variables             | Step 1  |       |       |      |      | Step 2  |       |              |            |     |
|-----------------------|---------|-------|-------|------|------|---------|-------|--------------|------------|-----|
|                       | $\beta$ | $t$   | $R^2$ | $F$  | $p$  | $\beta$ | $t$   | $\Delta R^2$ | $\Delta F$ | $p$ |
| <b>Model 1</b>        |         |       | 0.14  | 1.38 | 0.27 |         |       | 0.0          | 0.6        | 0.4 |
|                       |         |       |       |      |      |         |       | 2            | 1          | 4   |
| <i>EPN</i>            | 0.10    | 0.56  |       |      |      | 0.12    | 0.64  |              |            |     |
| <i>BF%</i>            | 0.02    | 0.09  |       |      |      | 0.02    | 0.10  |              |            |     |
| <i>Age</i>            | 0.35    | 1.90  |       |      |      | 0.36    | 1.95  |              |            |     |
| <i>EPN*BF%</i>        |         |       |       |      |      | -       | -0.78 |              |            |     |
|                       |         |       |       |      |      | 0.15    |       |              |            | 0   |
| <b>Model 2</b>        |         |       | 0.15  | 2.37 | 0.11 |         |       | 0.0          | 0.7        | .   |
|                       |         |       |       |      |      |         |       | 2            | 5          | 4   |
|                       |         |       |       |      |      |         |       |              |            | 0   |
| <i>EPN</i>            | 0.15    | 0.85  |       |      |      | 0.11    | 0.63  |              |            |     |
| <i>HOMA-IR</i>        | 0.37    | 2.08  |       |      |      | 0.32    | 1.76  |              |            |     |
| <i>Age</i>            |         |       |       |      |      | 0.32    | 1.73  |              |            |     |
| <i>EPN*HOMA-IR</i>    |         |       |       |      |      | -       | -0.86 |              |            |     |
|                       |         |       |       |      |      | 0.16    |       |              |            | 0   |
| <b>Model 3</b>        |         |       | 0.16  | 1.65 | 0.20 |         |       | 0.0          | 0.0        | .   |
|                       |         |       |       |      |      |         |       | 0            | 1          | 9   |
|                       |         |       |       |      |      |         |       |              |            | 1   |
| <i>eLPP</i>           | 0.19    | 1.00  |       |      |      | 0.18    | 0.93  |              |            |     |
| <i>BF%</i>            | 0.03    | 0.16  |       |      |      | 0.02    | 0.13  |              |            |     |
| <i>Age</i>            | 0.40    | 2.14  |       |      |      | 0.40    | 2.10  |              |            |     |
| <i>eLPP*BF%</i>       |         |       |       |      |      | -       | -0.12 |              |            |     |
|                       |         |       |       |      |      | 0.02    |       |              |            | 0   |
| <b>Model 4</b>        |         |       | 0.32  | 2.91 | 0.04 |         |       | 0.0          | 3.3        | .   |
|                       |         |       |       |      |      |         |       | 9            | 8          | 0   |
|                       |         |       |       |      |      |         |       |              |            | 8   |
| <i>eLPP</i>           | 0.11    | 0.61  |       |      |      | 0.12    | 0.69  |              |            |     |
| <i>HOMA-IR</i>        | 0.38    | 2.09  |       |      |      | 0.30    | 1.75  |              |            |     |
| <i>Age</i>            | 0.32    | 1.79  |       |      |      | 0.36    | 2.02  |              |            |     |
| <i>Race/Ethnicity</i> | 0.32    | 1.83  |       |      |      |         |       |              |            |     |
| <i>eLPP*HOMA-IR</i>   |         |       |       |      |      | -       | -1.84 |              |            |     |
|                       |         |       |       |      |      | 0.31    |       |              |            | 0   |
| <b>Model 5</b>        |         |       | 0.18  | 1.93 | 0.15 |         |       | 0.0          | 0.1        | .   |
|                       |         |       |       |      |      |         |       | 0            | 1          | 7   |
|                       |         |       |       |      |      |         |       |              |            | 4   |
| <i>mLPP</i>           | 0.24    | 1.32  |       |      |      | 0.23    | 1.26  |              |            |     |
| <i>BF%</i>            | -0.01   | -0.07 |       |      |      | -       | -0.13 |              |            |     |

|                |                       |               |               |                |             |               |     |     |
|----------------|-----------------------|---------------|---------------|----------------|-------------|---------------|-----|-----|
|                |                       |               |               |                | 0.02        |               |     |     |
|                | <i>Age</i>            | 0.41          | 2.21          |                | 0.41        | 2.19          |     |     |
|                | <i>mLPP*BF%</i>       |               |               |                | -           | -0.33         |     |     |
|                |                       |               |               |                | 0.06        |               |     | 0   |
| <b>Model 6</b> |                       |               | 0.34          | 3.22           | 0.03        |               | 0.0 | 1.3 |
|                |                       |               |               |                |             |               | 4   | 6   |
|                |                       |               |               |                |             |               |     | 2   |
|                |                       |               |               |                |             |               |     | 6   |
|                | <i>mLPP</i>           | 0.19          | 1.11          |                | 0.22        | 1.30          |     |     |
|                | <i>HOMA-IR</i>        | 0.37          | 2.05          |                | 0.42        | 2.29          |     |     |
|                | <i>Age</i>            | 0.33          | 1.92          |                | 0.38        | 2.15          |     |     |
|                | <i>Race/Ethnicity</i> | 0.33          | 1.93          |                | 0.31        | 1.81          |     |     |
|                | <i>mLPP*HOMA-IR</i>   |               |               |                | -           | -1.17         |     |     |
|                |                       |               |               |                | 0.21        |               |     | 0   |
| <b>Model 7</b> |                       |               | 0.24          | 1.95           | 0.13        |               | 0.1 | 4.7 |
|                |                       |               |               |                |             |               | 3   | 5   |
|                |                       |               |               |                |             |               |     | 0   |
|                |                       |               |               |                |             |               |     | 4   |
|                | <i>ILPP</i>           | 0.31          | 1.42          |                | 0.09        | 0.40          |     |     |
|                | <i>BF%</i>            | 0.25          | 1.13          |                | 0.28        | 1.39          |     |     |
|                | <i>Age</i>            | 0.37          | 2.11          |                | 0.39        | 2.34          |     |     |
|                | <i>Race/Ethnicity</i> | 0.37          | 1.79          |                | 0.42        | 2.15          |     |     |
|                | <i>ILPP*BF%</i>       |               |               |                | -           | -2.18         |     |     |
|                |                       |               |               |                | 0.44        |               |     | 0   |
| <b>Model 8</b> |                       |               | <b>0.44**</b> | <b>4.92***</b> | <b>0.00</b> |               | 0.1 | 6.3 |
|                |                       |               | *             |                | 5           |               | 2   | 3   |
|                |                       |               |               |                |             |               |     | 0   |
|                |                       |               |               |                |             |               |     | 2   |
|                | <i>ILPP</i>           | 0.43          | 2.44          |                | 0.28        | 1.63          |     |     |
|                | <i>HOMA-IR</i>        | <b>0.59**</b> | <b>3.28**</b> |                | <b>0.58</b> | <b>3.52**</b> |     |     |
|                |                       | *             | *             |                | ***         | *             |     |     |
|                | <i>Age</i>            | 0.29          | 1.91          |                | 0.28        | 2.02          |     |     |
|                | <i>Race/Ethnicity</i> | 0.52          | 2.97          |                | <b>0.49</b> | <b>3.07**</b> |     |     |
|                |                       |               |               |                | **          |               |     |     |
|                | <i>ILPP*HOMA-IR</i>   |               |               |                | -           | -2.52         |     |     |
|                |                       |               |               |                | 0.37        |               |     |     |

Table displays the results of each step of the hierarchical moderated regression analyses, which tested whether EPN or LPP voltage amplitudes and BF% or HOMA-IR moderated the mean reaction times after viewing negatively-valenced versus neutrally-valenced pictures. BF% = body fat percentage; eLPP = early latency late positive potential; EPN = early posterior negativity; HOMA-IR = homeostatic model assessment for insulin resistance; ILPP = late latency late positive potential; mLPP = middle latency late positive potential. \*\* and \*\*\* =  $p' \leq 0.0063$  and  $\leq 0.005$ , respectively.  $\beta$  shows standardized regression coefficients. Only statistically significant covariates ( $p \leq 0.10$ ) were included in each model.



**Figure 4.** Interaction plots depict how body fat percentage (a) and HOMA-IR (b) moderated the relationships between the voltage amplitudes of the LPP component during the late latency window and mean valence ratings in the contrasted Negative–Neutral picture condition. Predictor (late-window LPP component voltage amplitudes) and moderator (BF%, HOMA-IR values) variables were tested as continuous variables but are shown as tertiles for visualization. BF% = body fat percentage; HOMA-IR = homeostatic model assessment for insulin resistance; LPP = late positive potential; ms = milliseconds. \* and \*\*\* =  $p$ 's  $\leq 0.05$  and  $\leq 0.005$ , respectively. Amplitude deflections (lesser, average, greater) and BF% or HOMA-IR levels (low, medium, high) respectively reflect values at the 16<sup>th</sup>, 50<sup>th</sup>, and 84<sup>th</sup> percentiles of the total sample. Valence ratings represent the mean ratings of the magnitude of pleasantness or unpleasantness of images for each valence condition, where 1=“very positive,” 2=“somewhat positive,” 3=“somewhat negative,” and 4=“very negative,” which were subsequently contrasted as the difference between the mean valence ratings of neutrally-valenced pictures from the mean valence ratings of negatively-valenced pictures (i.e., Negative minus Neutral valence ratings). Early, middle, and

late latency windows of the LPP component = 400–800 ms, 800–1,200 ms, and 1,200–2,000 ms, respectively. For subjects with low BF% and low-to-medium HOMA-IR values, greater (i.e., more positive) LPP amplitudes during the late latency window were linked to less negative valence ratings in response to unpleasant versus neutral pictures.

### 3.6.2. Positive–Neutral Picture Condition

**Tables 7 and 8** present the results of the moderation analyses for predicting valence ratings and RTs, respectively, in the Positive–Neutral trials. Contrary to what was anticipated, BF% and IR were not found to moderate the associations between EPN or LPP amplitudes during any of the latency windows and affective processing scores for pleasant versus neutral stimuli.

**Table 7.** Hierarchical moderated regression results for Positive vs. Neutral valence ratings.

| Variables      | Step 1        |               |               |               |             | Step 2        |               |              |            |     |
|----------------|---------------|---------------|---------------|---------------|-------------|---------------|---------------|--------------|------------|-----|
|                | $\beta$       | $t$           | $R^2$         | $F$           | $p$         | $\beta$       | $t$           | $\Delta R^2$ | $\Delta F$ | $p$ |
| <b>Model 1</b> |               |               | <b>0.44**</b> | <b>6.82**</b> | <b>0.00</b> |               |               | 0.0          | 0.1        | 0.6 |
|                |               |               | *             | *             | <b>2</b>    |               |               | 0            | 7          | 9   |
| EPN            | -0.27         | -1.85         |               |               |             | -0.29         | -1.87         |              |            |     |
| BF%            | 0.32          | 2.11          |               |               |             | 0.32          | 2.05          |              |            |     |
| Race/Ethnicity | <b>0.62**</b> | <b>4.02**</b> |               |               |             | <b>0.61**</b> | <b>3.91**</b> |              |            |     |
|                | *             | *             |               |               |             | *             | *             |              |            |     |
| EPN*BF%        |               |               |               |               |             | 0.06          | 0.41          |              |            |     |
| <b>Model 2</b> |               |               | <b>0.41**</b> | <b>6.03**</b> | <b>0.00</b> |               |               | 0.0          | 0.0        | 0.7 |
|                |               |               | *             | *             | <b>3</b>    |               |               | 0            | 8          | 8   |
| EPN            | -0.32         | -2.10         |               |               |             | -0.32         | -2.07         |              |            |     |
| HOMA-IR        | 0.27          | 1.70          |               |               |             | 0.27          | 1.66          |              |            |     |
| Race/Ethnicity | <b>0.61**</b> | <b>3.84**</b> |               |               |             | <b>0.61**</b> | <b>3.72**</b> |              |            |     |
|                | *             | *             |               |               |             | *             | *             |              |            |     |
| EPN*HOMA-IR    |               |               |               |               |             | 0.04          | 0.29          |              |            |     |
| <b>Model 3</b> |               |               | <b>0.45**</b> | <b>5.09**</b> | <b>0.00</b> |               |               | 0.0          | 0.0        | 1.0 |
|                |               |               | *             | *             | <b>4</b>    |               |               | 0            | 0          | 0   |
| eLPP           | -0.15         | -0.93         |               |               |             | -0.15         | -0.86         |              |            |     |
| BF%            | 0.32          | 1.99          |               |               |             | 0.32          | 1.94          |              |            |     |
| Age            | -0.28         | -1.85         |               |               |             | -0.28         | -1.82         |              |            |     |
| Race/Ethnicity | <b>0.62**</b> | <b>3.99**</b> |               |               |             | <b>0.62**</b> | <b>3.91**</b> |              |            |     |
|                | *             | *             |               |               |             | *             | *             |              |            |     |
| eLPP*BF%       |               |               |               |               |             | 0.00          | -0.01         |              |            |     |
| <b>Model 4</b> |               |               | <b>0.43**</b> | <b>4.65**</b> | <b>0.00</b> |               |               | 0.0          | 0.0        | 0.9 |
|                |               |               |               |               | <b>6</b>    |               |               | 0            | 0          | 7   |
| eLPP           | -0.23         | -1.46         |               |               |             | -0.23         | -1.39         |              |            |     |
| HOMA-IR        | 0.28          | 1.68          |               |               |             | 0.28          | 1.64          |              |            |     |
| Age            | -0.32         | -2.00         |               |               |             | -0.32         | -1.96         |              |            |     |
| Race/Ethnicity | <b>0.64**</b> | <b>3.90**</b> |               |               |             | <b>0.64**</b> | <b>3.81**</b> |              |            |     |
|                | *             | *             |               |               |             | *             | *             |              |            |     |

|                          |               |               |               |               |             |               |               |     |     |     |
|--------------------------|---------------|---------------|---------------|---------------|-------------|---------------|---------------|-----|-----|-----|
| <i>eLPP*HOMA-IR</i>      |               |               |               |               | 0.01        | 0.04          |               |     |     |     |
| <b>Model 5</b>           |               |               | <b>0.45**</b> | <b>5.01**</b> | <b>0.00</b> |               |               | 0.0 | 1.0 | 0.3 |
|                          |               |               | *             | *             | <b>4</b>    |               |               | 2   | 0   | 3   |
| <i>mLPP</i>              | -0.12         | -0.81         |               |               |             | 0.04          | 0.23          |     |     |     |
| <i>BF%</i>               | 0.35          | 2.24          |               |               |             | 0.51          | 2.55          |     |     |     |
| <i>Age</i>               | -0.27         | -1.78         |               |               |             |               |               |     |     |     |
| <i>Race/Ethnicity</i>    | <b>0.62**</b> | <b>3.97**</b> |               |               |             | <b>0.67**</b> | <b>4.13**</b> |     |     |     |
|                          | *             | *             |               |               |             | *             | *             |     |     |     |
| <i>Physical Activity</i> |               |               |               |               |             | 0.36          | 1.81          |     |     |     |
| <i>mLPP*BF%</i>          |               |               |               |               |             | -0.17         | -1.00         |     |     |     |
| <b>Model 6</b>           |               |               | 0.32          | 4.11          | 0.02        |               |               | 0.0 | 2.0 | 0.1 |
|                          |               |               |               |               |             |               |               | 5   | 8   | 6   |
| <i>mLPP</i>              | -0.17         | -1.10         |               |               |             | 0.03          | 0.17          |     |     |     |
| <i>HOMA-IR</i>           | 0.29          | 1.76          |               |               |             | 0.46          | 2.32          |     |     |     |
| <i>Age</i>               | -0.29         | -1.83         |               |               |             |               |               |     |     |     |
| <i>Race/Ethnicity</i>    | <b>0.62**</b> | <b>3.77**</b> |               |               |             | <b>0.76**</b> | <b>4.24**</b> |     |     |     |
|                          | *             | *             |               |               |             | *             | *             |     |     |     |
| <i>Physical Activity</i> |               |               |               |               |             | 0.39          | 1.94          |     |     |     |
| <i>Sex</i>               |               |               |               |               |             | -0.33         | -1.91         |     |     |     |
| <i>mLPP*HOMA-IR</i>      |               |               |               |               |             | -0.25         | -1.44         |     |     |     |
| <b>Model 7</b>           |               |               | <b>0.54**</b> | <b>5.59**</b> | <b>0.00</b> |               |               | 0.0 | 0.2 | 0.6 |
|                          |               |               | *             | *             | <b>1</b>    |               |               | 1   | 7   | 1   |
| <i>ILPP</i>              | -0.29         | -1.76         |               |               |             | -0.31         | -1.81         |     |     |     |
| <i>BF%</i>               | 0.42          | 2.25          |               |               |             | 0.39          | 1.99          |     |     |     |
| <i>Age</i>               | -0.29         | -1.94         |               |               |             | -0.28         | -1.85         |     |     |     |
| <i>Physical Activity</i> | 0.30          | 1.76          |               |               |             | 0.32          | 1.79          |     |     |     |
| <i>Race/Ethnicity</i>    | <b>0.61**</b> | <b>4.00**</b> |               |               |             | <b>0.59**</b> | <b>3.72**</b> |     |     |     |
|                          | *             | *             |               |               |             | *             | *             |     |     |     |
| <i>ILPP*BF%</i>          |               |               |               |               |             | 0.08          | 0.52          |     |     |     |
| <b>Model 8</b>           |               |               | <b>0.47**</b> | <b>5.46**</b> | <b>0.00</b> |               |               | 0.0 | 0.1 | 0.7 |
|                          |               |               | *             | *             | <b>3</b>    |               |               | 0   | 2   | 3   |
| <i>ILPP</i>              | -0.32         | -2.03         |               |               |             | -0.30         | -1.80         |     |     |     |
| <i>HOMA-IR</i>           | 0.21          | 1.30          |               |               |             | 0.22          | 1.32          |     |     |     |
| <i>Age</i>               | -0.35         | -2.24         |               |               |             | -0.35         | -2.22         |     |     |     |
| <i>Race/Ethnicity</i>    | <b>0.54**</b> | <b>3.44**</b> |               |               |             | <b>0.54**</b> | <b>3.39**</b> |     |     |     |
|                          | *             | *             |               |               |             | *             | *             |     |     |     |
| <i>ILPP*HOMA-IR</i>      |               |               |               |               |             | -0.05         | -0.35         |     |     |     |

Table displays the results of each step of the hierarchical moderated regression analyses, which tested whether EPN or LPP voltage amplitudes and BF% or HOMA-IR moderated the mean valence ratings after viewing positively-valenced versus neutrally-valenced pictures. BF% = body fat percentage; eLPP = early latency late positive potential; EPN = early posterior negativity; HOMA-IR = homeostatic model assessment for insulin resistance; ILPP = late latency late positive potential; mLPP = middle latency late positive potential. \*\* and \*\*\* =  $p$ 's  $\leq 0.0063$  and  $\leq 0.005$ , respectively.  $\beta$  shows standardized regression coefficients. Only statistically significant covariates ( $p \leq 0.10$ ) were included in each model.

**Table 8.** Hierarchical moderated regression results for Positive vs. Neutral reaction times.

| Variables      | Step 1  |       |       |      |      | Step 2  |       |              |            |      |
|----------------|---------|-------|-------|------|------|---------|-------|--------------|------------|------|
|                | $\beta$ | $t$   | $R^2$ | $F$  | $p$  | $\beta$ | $t$   | $\Delta R^2$ | $\Delta F$ | $p$  |
| <b>Model 1</b> |         |       | 0.04  | 0.39 | 0.76 |         |       | 0.07         | 2.00       | 0.17 |
| EPN            | 0.15    | 0.77  |       |      |      | 0.21    | 1.08  |              |            |      |
| BF%            | -0.09   | -0.47 |       |      |      | -0.08   | -0.44 |              |            |      |
| EPN*BF%        |         |       |       |      |      | -0.27   | -1.41 |              |            |      |
| <b>Model 2</b> |         |       | 0.03  | 0.37 | 0.70 |         |       | 0.01         | 0.38       | 0.54 |
| EPN            | 0.16    | 0.82  |       |      |      | 0.16    | 0.84  |              |            |      |
| HOMA-IR        | -0.07   | -0.36 |       |      |      | -0.07   | -0.35 |              |            |      |
| EPN*HOMA-IR    |         |       |       |      |      | -0.12   | -0.62 |              |            |      |
| <b>Model 3</b> |         |       | 0.01  | 0.18 | 0.84 |         |       | 0.00         | 0.01       | 0.93 |
| eLPP           | 0.07    | 0.33  |       |      |      | 0.06    | 0.28  |              |            |      |
| BF%            | -0.07   | -0.35 |       |      |      | -0.07   | -0.35 |              |            |      |
| eLPP*BF%       |         |       |       |      |      | 0.02    | 0.09  |              |            |      |
| <b>Model 4</b> |         |       | 0.01  | 0.13 | 0.88 |         |       | 0.02         | 0.42       | 0.53 |
| eLPP           | 0.09    | 0.44  |       |      |      | 0.12    | 0.58  |              |            |      |
| HOMA-IR        | -0.03   | -0.18 |       |      |      | -0.04   | -0.23 |              |            |      |
| eLPP*HOMA-IR   |         |       |       |      |      | -0.13   | -0.65 |              |            |      |
| <b>Model 5</b> |         |       | 0.03  | 0.35 | 0.71 |         |       | 0.01         | 0.27       | 0.61 |
| mLPP           | 0.13    | 0.67  |       |      |      | 0.16    | 0.79  |              |            |      |
| BF%            | -0.07   | -0.39 |       |      |      | -0.10   | -0.48 |              |            |      |
| mLPP*BF%       |         |       |       |      |      | -0.11   | -0.52 |              |            |      |
| <b>Model 6</b> |         |       | 0.02  | 0.30 | 0.74 |         |       | 0.05         | 1.26       | 0.27 |
| mLPP           | 0.14    | 0.73  |       |      |      | 0.21    | 1.06  |              |            |      |
| HOMA-IR        | -0.04   | -0.22 |       |      |      | 0.00    | 0.00  |              |            |      |
| mLPP*HOMA-IR   |         |       |       |      |      | -0.23   | -1.12 |              |            |      |
| <b>Model 7</b> |         |       | 0.01  | 0.13 | 0.86 |         |       | 0.01         | 0.15       | 0.71 |
| ILPP           | -0.03   | -0.16 |       |      |      | -0.05   | -0.23 |              |            |      |
| BF%            | -0.11   | -0.51 |       |      |      | -0.13   | -0.60 |              |            |      |
| ILPP*BF%       |         |       |       |      |      | 0.08    | 0.38  |              |            |      |
| <b>Model 8</b> |         |       | 0.00  | 0.03 | 0.97 |         |       | 0.01         | 0.18       | 0.68 |
| ILPP           | 0.00    | 0.00  |       |      |      | 0.03    | 0.14  |              |            |      |
| HOMA-IR        | -0.05   | -0.24 |       |      |      | -0.03   | -0.17 |              |            |      |
| ILPP*HOMA-IR   |         |       |       |      |      | -0.09   | -0.42 |              |            |      |

Table displays the results of each step of the hierarchical moderated regression analyses, which tested whether EPN or LPP voltage amplitudes and BF% or HOMA-IR moderated the mean reaction times after viewing positively-valenced versus neutrally-valenced pictures. BF% = body fat percentage; eLPP = early latency late positive potential; EPN = early posterior negativity; HOMA-IR = homeostatic model assessment for insulin resistance; ILPP = late latency late positive potential; mLPP = middle latency late positive potential.  $\beta$  shows standardized regression coefficients. Only statistically significant covariates ( $p \leq 0.10$ ) were included in each model.

### 3.6.3. Negative–Positive Picture Condition

The results of the moderation analyses are displayed in **Table 9** for valence ratings and **Table 10** for RTs in the Negative–Positive condition. In contrast with what was hypothesized, BF% and IR did not moderate the links between EPN or LPP amplitude deflections during any of the latency windows and affective processing parameters of unpleasant stimuli relative to pleasant.

**Table 9.** Hierarchical moderated regression results for Negative vs. Positive valence ratings.

| Variables         | Step 1        |               |                |                |              | Step 2 |       |              |            |      |
|-------------------|---------------|---------------|----------------|----------------|--------------|--------|-------|--------------|------------|------|
|                   | $\beta$       | $t$           | $R^2$          | $F$            | $p$          | $B$    | $t$   | $\Delta R^2$ | $\Delta F$ | $p$  |
| <b>Model 1</b>    |               |               | <b>0.41***</b> | <b>5.96***</b> | <b>0.003</b> |        |       | 0.02         | 1.04       | 0.32 |
| EPN               | 0.34          | 2.09          |                |                |              | 0.30   | 1.84  |              |            |      |
| BF%               | 0.35          | 2.23          |                |                |              | 0.37   | 2.33  |              |            |      |
| Race/Ethnicity    | -0.42         | -2.51         |                |                |              | -0.36  | -1.98 |              |            |      |
| EPN*BF%           |               |               |                |                |              | 0.17   | 1.02  |              |            |      |
| <b>Model 2</b>    |               |               | 0.35           | 4.68           | 0.01         |        |       | 0.05         | 2.15       | 0.16 |
| EPN               | 0.41          | 2.41          |                |                |              | 0.46   | 2.71  |              |            |      |
| HOMA-IR           | 0.25          | 1.51          |                |                |              | 0.25   | 1.54  |              |            |      |
| Race/Ethnicity    | -0.47         | -2.67         |                |                |              | -0.40  | -2.29 |              |            |      |
| EPN*HOMA-IR       |               |               |                |                |              | 0.25   | 1.47  |              |            |      |
| <b>Model 3</b>    |               |               | 0.32           | 4.07           | 0.02         |        |       | 0.00         | 0.02       | 0.89 |
| eLPP              | 0.12          | 0.68          |                |                |              | 0.14   | 0.74  |              |            |      |
| BF%               | <b>0.61**</b> | <b>3.02**</b> |                |                |              | 0.43   | 2.36  |              |            |      |
| Physical Activity | 0.33          | 1.72          |                |                |              |        |       |              |            |      |
| eLPP*BF%          |               |               |                |                |              | 0.02   | 0.13  |              |            |      |
| <b>Model 4</b>    |               |               | 0.26           | 3.04           | 0.05         |        |       | 0.02         | 0.50       | 0.49 |
| eLPP              | 0.15          | 0.83          |                |                |              | 0.10   | 0.52  |              |            |      |
| HOMA-IR           | 0.22          | 1.24          |                |                |              | 0.28   | 1.40  |              |            |      |
| Sex               | -0.36         | -2.08         |                |                |              | -0.38  | -2.14 |              |            |      |
| eLPP*HOMA-IR      |               |               |                |                |              | -0.14  | -0.71 |              |            |      |
| <b>Model 5</b>    |               |               | 0.03           | 0.12           | 0.99         |        |       | 0.06         | 2.11       | 0.16 |
| mLPP              | 0.18          | 1.07          |                |                |              | 0.17   | 1.00  |              |            |      |
| BF%               | <b>0.60**</b> | <b>3.06**</b> |                |                |              | 0.38   | 2.23  |              |            |      |
| Physical Activity | 0.33          | 1.75          |                |                |              |        |       |              |            |      |
| mLPP*BF%          |               |               |                |                |              | 0.24   | 1.45  |              |            |      |

|                       |       |       |      |      |      |       |       |      |      |      |
|-----------------------|-------|-------|------|------|------|-------|-------|------|------|------|
| <b>Model 6</b>        |       |       | 0.27 | 3.25 | 0.04 |       |       | 0.00 | 0.07 | 0.80 |
| <i>mLPP</i>           | 0.19  | 1.09  |      |      |      | 0.18  | 0.97  |      |      |      |
| <i>HOMA-IR</i>        | 0.24  | 1.38  |      |      |      | 0.22  | 1.23  |      |      |      |
| <i>Sex</i>            | -0.34 | -1.95 |      |      |      | -0.34 | -1.93 |      |      |      |
| <i>mLPP*HOMA-IR</i>   |       |       |      |      |      | 0.05  | 0.26  |      |      |      |
| <b>Model 7</b>        |       |       | 0.33 | 4.33 | 0.01 |       |       | 0.13 | 5.77 | 0.02 |
| <i>ILPP</i>           | -0.16 | -1.00 |      |      |      | -0.16 | -1.05 |      |      |      |
| <i>BF%</i>            | 0.39  | 2.34  |      |      |      | 0.39  | 2.51  |      |      |      |
| <i>Race/Ethnicity</i> | -0.33 | -1.92 |      |      |      | -0.36 | -2.27 |      |      |      |
| <i>ILPP*BF%</i>       |       |       |      |      |      | 0.35  | 2.40  |      |      |      |
| <b>Model 8</b>        |       |       | 0.24 | 2.78 | 0.06 |       |       | 0.04 | 1.27 | 0.27 |
| <i>ILPP</i>           | -0.05 | -0.32 |      |      |      | -0.15 | -0.86 |      |      |      |
| <i>HOMA-IR</i>        | 0.26  | 1.53  |      |      |      | 0.18  | 1.00  |      |      |      |
| <i>Sex</i>            | -0.38 | -2.18 |      |      |      |       |       |      |      |      |
| <i>Race/Ethnicity</i> |       |       |      |      |      | -0.39 | -2.11 |      |      |      |
| <i>ILPP*HOMA-IR</i>   |       |       |      |      |      | 0.19  | 1.13  |      |      |      |

Table displays the results of each step of the hierarchical moderated regression analyses, which tested whether EPN or LPP voltage amplitudes and BF% or HOMA-IR moderated the mean valence ratings after viewing negatively-valenced versus positively-valenced pictures. BF% = body fat percentage; eLPP = early latency late positive potential; EPN = early posterior negativity; HOMA-IR = homeostatic model assessment for insulin resistance; ILPP = late latency late positive potential; mLPP = middle latency late positive potential. \*\* and \*\*\* =  $p \leq 0.0063$  and  $\leq 0.005$ , respectively.  $\beta$  shows standardized regression coefficients. Only statistically significant covariates ( $p \leq 0.10$ ) were included in each model.

**Table 10.** Hierarchical moderated regression results for Negative vs. Positive reaction times.

| Variables             | Step 1  |       |       |      |      | Step 2  |       |              |            |      |
|-----------------------|---------|-------|-------|------|------|---------|-------|--------------|------------|------|
|                       | $\beta$ | $t$   | $R^2$ | $F$  | $p$  | $\beta$ | $t$   | $\Delta R^2$ | $\Delta F$ | $p$  |
| <b>Model 1</b>        |         |       | 0.36  | 3.52 | 0.02 |         |       | 0.03         | 0.89       | 0.36 |
| <i>EPN</i>            | -0.48   | -2.82 |       |      |      | -0.35   | -2.05 |              |            |      |
| <i>BF%</i>            | 0.13    | 0.77  |       |      |      | 0.02    | 0.14  |              |            |      |
| <i>Age</i>            | 0.33    | 2.04  |       |      |      | 0.36    | 2.06  |              |            |      |
| <i>Race/Ethnicity</i> | 0.36    | 1.98  |       |      |      |         |       |              |            |      |
| <i>EPN*BF%</i>        |         |       |       |      |      | -0.16   | -0.94 |              |            |      |
| <b>Model 2</b>        |         |       | 0.41  | 4.30 | 0.01 |         |       | 0.00         | 0.17       | 0.68 |
| <i>EPN</i>            | -0.44   | -2.64 |       |      |      | -0.45   | -2.63 |              |            |      |
| <i>HOMA-IR</i>        | 0.27    | 1.62  |       |      |      | 0.27    | 1.56  |              |            |      |
| <i>Age</i>            | 0.29    | 1.84  |       |      |      | 0.31    | 1.86  |              |            |      |
| <i>Race/Ethnicity</i> | 0.39    | 2.28  |       |      |      | 0.37    | 2.06  |              |            |      |
| <i>EPN*HOMA-IR</i>    |         |       |       |      |      | -0.07   | -0.41 |              |            |      |
| <b>Model 3</b>        |         |       | 0.18  | 1.94 | 0.15 |         |       | 0.01         | 0.38       | 0.54 |
| <i>eLPP</i>           | -0.25   | -1.31 |       |      |      | -0.23   | -1.18 |              |            |      |
| <i>BF%</i>            | 0.11    | 0.59  |       |      |      | 0.13    | 0.67  |              |            |      |
| <i>Age</i>            | 0.35    | 1.97  |       |      |      | 0.33    | 1.75  |              |            |      |

|                     |       |       |      |      |      |       |       |      |      |      |
|---------------------|-------|-------|------|------|------|-------|-------|------|------|------|
| <i>eLPP*BF%</i>     |       |       |      |      | 0.12 | 0.62  |       |      |      |      |
| <b>Model 4</b>      |       |       | 0.27 | 3.24 | 0.04 |       |       | 0.03 | 1.10 | 0.30 |
| <i>eLPP</i>         | -0.31 | -1.78 |      |      |      | -0.25 | -1.32 |      |      |      |
| <i>HOMA-IR</i>      | 0.34  | 1.89  |      |      |      | 0.33  | 1.63  |      |      |      |
| <i>Age</i>          | 0.29  | 1.71  |      |      |      |       |       |      |      |      |
| <i>eLPP*HOMA-IR</i> |       |       |      |      |      | 0.20  | 1.05  |      |      |      |
| <b>Model 5</b>      |       |       | 0.14 | 1.37 | 0.27 |       |       | 0.00 | 0.01 | 0.94 |
| <i>mLPP</i>         | -0.09 | -0.48 |      |      |      | -0.09 | -0.48 |      |      |      |
| <i>BF%</i>          | 0.05  | 0.28  |      |      |      | 0.05  | 0.26  |      |      |      |
| <i>Age</i>          | 0.35  | 1.89  |      |      |      | 0.35  | 1.81  |      |      |      |
| <i>mLPP*BF%</i>     |       |       |      |      |      | 0.01  | 0.07  |      |      |      |
| <b>Model 6</b>      |       |       | 0.12 | 1.78 | 0.19 |       |       | 0.07 | 2.35 | 0.14 |
| <i>mLPP</i>         | -0.14 | -0.78 |      |      |      | -0.21 | -1.12 |      |      |      |
| <i>HOMA-IR</i>      | 0.34  | 1.83  |      |      |      | 0.26  | 1.41  |      |      |      |
| <i>mLPP*HOMA-IR</i> |       |       |      |      |      | 0.29  | 1.53  |      |      |      |
| <b>Model 7</b>      |       |       | 0.19 | 2.00 | 0.14 |       |       | 0.01 | 0.27 | 0.61 |
| <i>ILPP</i>         | -0.25 | -1.37 |      |      |      | -0.24 | -1.30 |      |      |      |
| <i>BF%</i>          | 0.03  | 0.19  |      |      |      | 0.04  | 0.21  |      |      |      |
| <i>Age</i>          | 0.41  | 2.25  |      |      |      | 0.39  | 2.02  |      |      |      |
| <i>ILPP*BF%</i>     |       |       |      |      |      | 0.10  | 0.52  |      |      |      |
| <b>Model 8</b>      |       |       | 0.23 | 2.63 | 0.07 |       |       | 0.01 | 0.33 | 0.57 |
| <i>ILPP</i>         | -0.23 | -1.29 |      |      |      | -0.23 | -1.27 |      |      |      |
| <i>HOMA-IR</i>      | 0.22  | 1.25  |      |      |      | 0.23  | 1.25  |      |      |      |
| <i>Age</i>          | 0.36  | 1.99  |      |      |      | 0.35  | 1.85  |      |      |      |
| <i>ILPP*HOMA-IR</i> |       |       |      |      |      | 0.10  | 0.58  |      |      |      |

Table displays the results of each step of the hierarchical moderated regression analyses, which tested whether EPN or LPP voltage amplitudes and BF% or HOMA-IR moderated the mean reaction times after viewing negatively-valenced versus positive-valenced pictures. BF% = body fat percentage; eLPP = early latency late positive potential; EPN = early posterior negativity; HOMA-IR = homeostatic model assessment for insulin resistance; ILPP = late latency late positive potential; mLPP = middle latency late positive potential.  $\beta$  shows standardized regression coefficients. Only statistically significant covariates ( $p \leq 0.10$ ) were included in each model.

#### 4. Discussion

The electrophysiological mechanisms underlying how adiposity and especially IR influence the link between brain potentials and affective processing remain scarcely investigated. The paucity of studies that have investigated such interrelationships, however, have most frequently done so using fMRI (e.g., [12,16,62,63]). The single study that utilized EEG, however, assessed middle-aged adults [64]. Yet, considering the advantages of EEG in comparison of fMRI, including EEG's superior temporal resolution and less costly utilization [20,21], it is crucial to test whether EEG is a sufficient alternative neuroimaging approach for testing such interrelationships. Therefore, EEG was utilized to investigate whether obesity and/or IR moderated the relationship between brain potentials and affective processing in young adults.

In the Negative-Neutral trials, young adults without obesity or IR displayed significantly greater LPP amplitudes during the late latency window, in contrast with what was expected. However, among these participants, larger LPP responses were linked to less negative ratings of unpleasant images, suggesting that stronger neural engagement was associated with a dampening of

negative emotional experience. This pattern further implies that IR may be one mechanism through which obesity alters the neural basis of prolonged negative affective processing. By contrast, this relationship was absent in young adults with obesity and/or IR, indicating a disruption in the typical coupling between neural activity and emotional evaluation. Ordinarily, increased activity in the dorsolateral prefrontal cortex in response to unpleasant stimuli reflects more top-down control to suppress affective responses [65], with successful down-regulation of negatively-valenced stimuli being subsequently manifested as reduced LPP amplitudes [66]. Hence, an inverse relationship between late-window LPP amplitudes and valence ratings (where lower values indicated less negative valence ratings) to unpleasant stimuli in lean, insulin-sensitive young adults was unexpected. In spite of this, the finding of an inverse LPP amplitudes–valence ratings correlation is in congruence with findings from several studies (e.g., [67–70]). Rather than indicating an unsuccessful dampening of negatively-valenced stimuli and a concomitant enhancement of negative affective processing, higher LPP amplitudes in the late latency window may instead reflect more effortful spontaneous emotion regulation, as previously suggested [67,70]. Taken together, these findings suggest that lean, insulin-sensitive individuals may attenuate negative affective processing of unpleasant stimuli through greater cognitive effort to regulate these negatively-valenced stimuli spontaneously. Additional longitudinal studies are critical to gain a clearer understanding of the electrophysiological mechanisms underlying how adiposity, IR, and associated brain structural and functional alterations influence negative affective processing.

In the contrasted Positive–Neutral valence trial, obesity and IR were not found to moderate the links between LPP amplitudes across any of the latency windows and affective processing scores, implying that neural responses to pleasant stimuli and associated positive affective processing may be spared from obesity- and/or IR-induced brain structural and functional alterations in young adulthood. These results are in concurrence with some [71,72], but not all [73,74], previous findings. Moreover, obesity and IR did not moderate the relationships between brain potentials and underlying affective processing in the contrasted Negative–Positive condition. This suggests that, similarly to the early-window LPP, late-window LPP may also be more strongly driven by arousal than by valence and, thus, may not be valence-biased [27,75,76], although this contrasts some prior findings (e.g., [37]). Inconsistencies exist in the body of literature that has compared the LPP responses to unpleasant versus pleasant stimuli, with some studies finding no differences in LPP amplitudes between either emotional condition across a wide range of age groups [77,78] and other studies finding valence-specific differentiation, although these findings appeared to be arousal-dependent [37,76]. Significant methodological, LPP quantification, and sample heterogeneity may partially account for such discordant findings. In addition, the null results found in this study could be in part explained by differences in the neurocircuitry involved between negative and positive affective processing. Specifically, the processing of negative emotions more heavily involves activity from the amygdala, anterior insula, anterior cingulate cortex, visual cortex, as well as the dorsolateral and ventrolateral prefrontal cortices [79,80], whereas the processing of positive emotions more substantially relies upon activity in the medial prefrontal cortex, orbitofrontal cortex, ventral striatum, nucleus accumbens, and ventral tegmental area [81,82]. Hence, the brain structures involved in positive affective processing may be less susceptible to obesity- and/or IR-linked structural and functional alterations compared to the brain structures that modulate negative affective processing. Nevertheless, future studies are crucial to better understand how obesity and IR may impact brain potentials and positive affective processing.

Finally, BF% and HOMA-IR did not moderate the links between EPN amplitudes and affective processing parameters across any of the contrasted valence conditions. Hence, this suggests that obesity and IR do not impact visual attention allocation to emotional versus neutral stimuli in young adulthood. To our knowledge, this study is the first to investigate whether obesity and/or IR moderated the relationship between EPN amplitudes and affective processing. Nonetheless, these results are not surprising when considering that the scalp distribution of the EPN component over the occipitotemporal sites reflects visual cortical activity [83], a largely insulin-independent region

[84]. One study demonstrated this by showing that insulin infusion had no effect on subsequent visual evoked potentials [85]. Nevertheless, additional research is needed to clarify whether obesity and IR influence EPN amplitudes and underlying visual attention allocation to emotional versus neutral stimuli.

This study was not without limitations. First, the sample size was small, hence limiting the generalizability of this study's findings. Second, the utilization of the EEG neuroimaging modality in conjunction with the cross-sectional study design barred any causal implications. Third, neural activity measured during exposure to emotional images in a laboratory setting may not necessarily translate to real-world settings. Fourth, HOMA-IR is an index of short-term IR and may not have accurately reflected chronic IR in all subjects.

This study also included several strengths. First, the central research questions were novel. Second, EEG provided an inexpensive, non-invasive neuroimaging approach which showed findings that were largely congruent with earlier fMRI findings. Third, body composition was measured directly via DEXA, which provided a significantly more accurate quantification of BF% in comparison to indirect measures (e.g., BMI [86]).

## 5. Conclusions

Obesity and IR moderate the relationship between brain potentials and negative affective processing, but not positive affective processing, in young adults. Specifically, increased neural responses to unpleasant stimuli were associated with attenuated negative affective processing in lean and insulin sensitive young adults, whereas no such correlation was found in young adults with obesity or IR. This finding suggests that higher body fat levels may disrupt the typical coupling between neural activity and emotional evaluation, and IR may be one mechanism to explain how obesity alters negative affective processing. These data furthermore support prior findings that obesity and IR are both risk factors for mood disorders in young adulthood. In addition, the degree of reflexive visual attention to emotional stimuli is not moderated by obesity or IR in young adulthood. Finally, EEG appears to be a sufficient neuroimaging approach for investigating these interrelationships. Additional work is warranted to investigate these interrelationships long-term using EEG, particularly for positive affective processing.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/doi/s1>, Figures S1a–f: Non-differenced Negative, Neutral, and Positive EPN and LPP waveforms by body fat percentage; Figures S2a–f: Non-differenced Negative, Neutral, and Positive EPN and LPP waveforms by insulin resistance levels.

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## Abbreviations

The following abbreviations are used in this manuscript:

|                |  |
|----------------|--|
| BF%            | Body fat percentage                                  |
| BMI            | Body mass index                                      |
| BP             | Blood pressure                                       |
| DEXA/DXA       | Dual-energy X-ray absorptiometry scan                |
| EEG            | Electroencephalography                               |
| eLPP           | Late positive potential in the early latency window  |
| EPN            | Early posterior negativity                           |
| ERP            | Event-related potential                              |
| fMRI           | Functional magnetic resonance imaging                |
| Hemoglobin A1c | Glycated hemoglobin                                  |
| HOMA-IR        | Homeostatic model assessment for insulin resistance  |
| IR             | Insulin resistance/resistant                         |
| IS             | Insulin sensitivity/sensitive                        |
| ILPP           | Late positive potential in the late latency window   |
| LPP            | Late positive potential                              |
| mLPP           | Late positive potential in the middle latency window |
| ms             | Milliseconds   |
| RT             | Reaction time  |

## Appendix A

**Table A1.** International Affective Picture System task photo identification numbers by valence condition.

| Negative                | Neutral                 | Positive                |
|-------------------------|-------------------------|-------------------------|
| 3030, 3060, 3071, 3100, | 2372, 2383, 2514, 2840, | 1340, 1463, 2165, 2306, |
| 3102, 3130, 3150, 3170, | 5410, 6150, 6900, 7000, | 2374, 4603, 4611, 4652, |
| 6020, 6230, 6313, 6570, | 7002, 7006, 7009, 7010, | 4656, 4810, 5202, 5611, |
| 9040, 9140, 9181, 9253, | 7035, 7080, 7130, 7170, | 5764, 6250, 7200, 7250, |
| 9265, 9320, 9420, 9433, | 7175, 7233, 7491, 7550, | 7508, 8118, 8251, 8500, |
| 9570, 9571              | 7705                    | 9400                    |

A Table displays the photo identification number for each photo used in the negatively-, neutrally-, and positively-valenced picture conditions during the International Affective Picture System task.

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