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Association between central obesity and executive function as assessed by stroop task performance: A functional near-infrared spectroscopy study

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Recent studies have suggested a link between executive function (EF) and obesity. Studies often adopt body mass index (BMI), which reflects the distribution of subcutaneous fat, as the sole marker of obesity; however, BMI is inappropriate to distinguish central obesity, which indicates the centralized distribution of visceral fat. Visceral fat compared with subcutaneous fat represents greater relative lipid turnover and may increase the risk of cognitive decline in older adults. However, the relationship between EF and central obesity is largely unknown, particularly in young adults. Therefore, we used waist circumference (WC) as a marker of central obesity and investigated different sensitivities between BMI and WC in the brain function. A total of 26 healthy young adults (aged 18–25 years; 42% female) underwent functional near-infrared spectroscopy assessments. EF was assessed using the Stroop task, which is a classical measurement of EF. A significant Stroop effect was observed in the behavioral and hemodynamic data. In addition, we observed that behavioral interference on the Stroop task varied much more in subjects with higher BMI and WC than those subjects with lower. Elevated BMI and WC were associated with a decreased hemodynamic response during the Stroop task specifically in the prefrontal cortex (PFC). Compared to BMI, WC was more closely connected with inhibitory control and revealed right lateralized PFC activation. Our findings suggest that WC is a reliable indicator of brain function in young adults and propose a relationship between EF and central obesity.

Keywords: Executive function; central obesity; fNIRS; young adult.

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1. Introduction

Over the past 30 years, overweight and obesity have risen dramatically worldwide.[1] Data from the World Health Organization suggest that overweight and obesity lead to health consequences such as cancers, cardiovascular disease and metabolic disease.[2] Recent studies have suggested that obesity is an important predictor of structural brain impairments,[3] abnormal brain function[4] and decreased behavioral performance in tests of executive function (EF).[5] Body mass index (BMI) has been widely used in previous studies as a sole marker of obesity.[6] However, this anthropometric measurement reflects the overall distribution of subcutaneous fat and is inappropriate to distinguish centralized distribution of visceral fat or central obesity.[7,8] Rather, waist circumference (WC) has been suggested as the best anthropometric measurement of central obesity.[9]

Central obesity is representative of deposited visceral fat, which might have a negative effect on metabolic activity.[10] Metabolic mechanisms mediate the relationship between visceral fat and the central nervous system, and might lead to dementia later in life.[11] One recent study revealed that WC is independently related to the behavioral performance in EF tests.[12] Gonzales[13] and colleagues further reported an inverse relationship between WC and brain function in regions involved in EF. To date, only a handful of studies have investigated the direct relationship between central obesity and EF. The existing research has predominantly focused on middle-aged or older adults.[13–15] However, few studies have examined the direct relationship between central obesity and abnormal brain function in young adults, which represents a high-risk group for metabolic syndrome.[16] Moreover, Fitzpatrick and colleagues reviewed previously published studies and observed that BMI may not always be related to the behavioral performance in EF tests. These mixed findings indicate the need for further research to examine the relationship between obesity and EF.[17]

Considering obese subjects during scanning, several studies have used a promising non-invasive neuroimaging technique, functional near-infrared spectroscopy (fNIRS), to study obesity-related brain function.[18–20] FNIRS measures the concentration changes of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) in specific brain regions and provides acceptable spatial precision for brain activation.[21] To our knowledge, there have been no fNIRS studies examining the relationship between EF and obesity or central obesity.

In summary, the relationship between obesity (particularly central obesity) and abnormal brain function in young adults is largely unknown. Consequently, we preliminarily examined the relationship between EF and two anthropometric measurements of obesity (BMI and WC) in young adults, and further compared the different sensitivities between BMI and WC in the brain function. In the present study, fNIRS data were collected during the Stroop task in a sample of overweight and obese individuals. We hypothesized that subjects with a higher BMI and WC would reveal a lower prefrontal cortex (PFC) activation during the Stroop task than the subjects with a lower BMI and WC.[22]

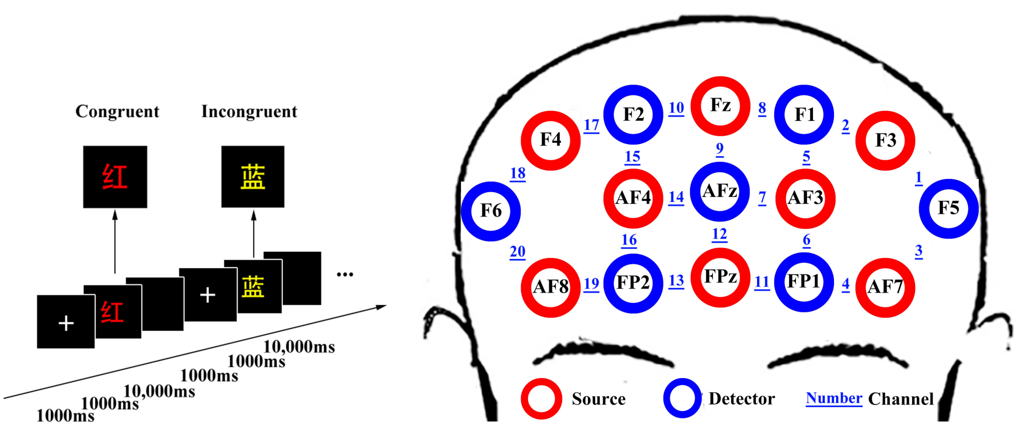
2. Methods

2.1. *Subjects*

A total of 32 young adults (aged 18–25 years; 47% female) were recruited. BMI (weight divided by the square of height, $\mathrm{kg/m^2}$) and WC (cm) were measured in all subjects. Based on the BMI cut-off points for obesity in the Chinese population, overweight ($24 \leq \mathrm{BMI} < 28\,\mathrm{kg/m^2}$) and obese ($\mathrm{BMI} \geq 28\,\mathrm{kg/m^2}$) subjects were defined. Furthermore, we adopted the International Diabetes Federation's cut-off points for the Chinese population to distinguish central obesity: the non-central obese (WC $\leq$90 cm in males or $\leq$80 cm in females) and the central obese (WC $>$90 cm in males or $>$80 cm in females).[23] Subjects were required to sign an informed consent form. We used the following inclusion criteria: (1) native speaker of Chinese, (2) right-handed, (3) normal or corrected-to-normal vision with normal color vision and (4) no history of a mental disorder. The study was approved by the Ethics Committee of Wuhan Sport University.

2.2. *Stimuli and procedure*

The Stroop task was conducted in a quiet room lit by daylight to evoke PFC activity.[24,25] The subjects were visually instructed on all task procedures and were cued on a PC display that was placed in front of them. The event-related Stroop task was adopted in the current study and designed using E-prime 2.0 (Psychology Software Tools, Pittsburgh, PA).



(a) (b)

Fig. 1. (a) The design of the experimental runs and instance for congruent and incongruent conditions. 红 means red, 蓝 means blue. Subjects were instructed to decide whether the semantic meaning of the word corresponded to the color of the word. (b) Spatial profiles of fNIRS probe. The red circle indicates the 8 optical sources and the blue circle indicates the 7 detectors, the blue numbers (1 to 20) indicate the fNIRS channels. Optical sources and detectors probe on the international 10–20 standard positions.

In the Stroop task, the subjects were instructed to respond to the color of the stimulus while ignoring its semantic meaning. The stimuli included four Chinese color words 红, 黄, 蓝 and 绿 (meaning "red", "yellow", "blue" and "green", respectively). The congruent and incongruent conditions are displayed in Fig. 1(a). For the congruent condition, the meaning of the stimulus was consistent with the color of the stimulus (e.g., the word "yellow" printed in yellow). For the incongruent condition, the color of the stimulus did not denote the meaning of the stimulus (e.g., the word "red" printed in blue). When the color of the stimulus was inconsistent with its semantic meaning, this created a conflict condition. This conflict leads to a reaction time (RT) delay or cognitive process between the incongruent condition and congruent condition, which is referred to as the Stroop effect or Stroop interference. Interference in behavioral and hemodynamic data was used to indicate EF. Therefore, the interference value between the incongruent condition and congruent condition, due to the Stroop effect, was adopted to clarify the relationship between obesity and EF. Based on the findings of previous studies, we can conclude that obesity may influence behavioral and cognitive performance.

The experimental procedure is displayed in Fig. 1(a). The test consisted of 48 judgment trials (24 congruent trials and 24 incongruent trials). For each trial, a white cross was displayed on the screen for 1000 ms, and then the color-word stimulus was displayed on the screen for 1000 ms, with an interval blank screen for 10,000 ms. The order of the trials was random. All subjects received practice trials prior to the formal experiment and were instructed to react as quickly as possible.

2.3. *Date recording*

The multi-channel continuous wave fNIRS system NIRScout (NIRX Medical Technologies LLC, USA) was adopted to monitor hemodynamic responses in the present study. The fNIRS probe consisted of 8 dual-wavelength sources (760 and 850 nm) and 7 optical detectors (Fig. 1(b)). The distance between the source and the detector was 3 cm. Figure 1(b) shows the arrangement of the probes. The probes covered the prefrontal area and, when adjusted to the 10/10 EEG positions, 20 channels were obtained. Using the probabilistic estimation method,[26–28] we estimated the projection of the electrode coordinates in the brain region. Therefore, we presumed that the fNIRS channels covered part of the bilateral frontopolar area (FPA), bilateral ventrolateral PFC (VLPFC) and bilateral dorsolateral PFC (DLPFC).

Optical data were converted into hemoglobin signals in an arbitrary unit using the modified Beer–Lambert Law. The sampling rate was 7.8 Hz. The hemoglobin data were bandpass filtered between 0.01 Hz and 0.3 Hz to remove baseline drift and physiological noise (e.g., heartbeats). Each subject's hemodynamic data were averaged across 24 trials for each condition. The mean concentration change of the oxy-Hb and deoxy-Hb signals during 0–12 s across the different subjects, conditions and channels were recorded.

2.4. *Statistical analyses*

Statistical analyses were performed using SPSS 17.0 (SPSS Inc., Chicago, USA). Significance for the RT and Error Rate for different conditions was analyzed using a one-way ANOVA. We then examined whether the differences in BMI and WC were related to the Stroop interference. The trials with no response or extreme value (mean RTs > ± 3SD) and the subjects with large error rate (>8%) were eliminated from the behavioral data analysis.[29] The mean hemodynamic data for the congruent condition and that for the incongruent were compared using paired t-test. Neighboring significant channels were combined in a brain region based on LBPA40.[30] Next, the mean hemodynamic changes during the 12s task period were compared between different BMI or WC categories for each region by unpaired Student's t-test. False discovery rate (FDR) has been used to correct the significance of analysis in multi-channel measurements, which the rho values reached FDR-corrected significance level of $p < 0.05$.[31] Additionally, we performed χ^2 tests for gender in different BMI or WC categories.

3. Results

3.1. *Characteristics*

We investigated the demographic characteristics of all subjects. The demographic characteristics of subjects in the present study are shown in Tables 1 and 2 in term of BMI and WC categories. No significant differences were observed for gender (BMI category: $\chi^2 = 0.5359$, $p = 0.4641$; WC category: $\chi^2 = 1.1294$, $p = 0.2875$).

Table 1. Characteristics of subjects across BMI categories.

	24≤ BMI <28	BMI ≥28
N	17	15
Men (%)	47	60
age	19.77 ± 2.44	19.94 ± 2.01
WC in male(cm)	85.5 ± 3.96	89.00 ± 2.59
WC in female(cm)	78.44 ± 2.07	82.16 ± 1.83

Note: Data are mean ± SD.

Table 2. Characteristics of subjects across WC categories.

	WC ≤90 cm in males or ≤80 cm in females	WC >90 cm in males or >80 cm in females
N	16	16
Men (%)	62	43
Age (year)	20.15 ± 2.37	19.53 ± 1.68
BMI (kg/m^2)	27.91 ± 3.25	31.36 ± 3.96

Note: Data are mean ± SD.

3.2. *Behavioral data*

The average RT and Error Rate for the congruent condition (920.13 ± 153.22 ms; 1.17 ± 2.38%) were less than those for the incongruent condition (1018.43 ± 131.21 ms; 2.99 ± 3.16%). The one-way ANOVA revealed a significant effect of condition ($F = 7.619$, $df = 1$, $p < 0.01$; $F = 6.562$, $df = 1$, $p < 0.05$). A significant Stroop effect was induced by different task conditions.

To illuminate the effect of BMI and WC on EF, the RT interference (the incongruent RT minus the congruent RT) was calculated. We first analyzed the relationship between the RT interference and BMI. We then examined the relationship between the RT interference and WC. Regarding BMI, the obese subjects revealed a significantly greater Stroop interference than the overweight subjects (77.96 ± 40.78 versus 42.06 ± 40.26, $t[31] = 2.488$, $p < 0.05$). Regarding WC, the central obese subjects revealed a significantly greater Stroop interference than the non-central obese subjects (79.44 ± 38.18 versus 42.78 ± 42.65, $t[31] = 2.566$, $p < 0.05$). Therefore, both BMI and WC were related to the Stroop test performance.

3.3. *NIRS results*

The overall average time courses of the oxy-Hb and deoxy-Hb responses for all the subjects during the Stroop task across all 20 channels are shown in Fig. 2. Regarding deoxy-Hb, there was no significant difference between the incongruent and congruent condition. Therefore, we excluded deoxy-Hb from the subsequent analyses.

A significant Stroop effect was found in 12 channels. We converted all of the corresponding electrodes to the standard Montreal Neurological Institute (MNI) coordinates using a probabilistic estimation method.[32,33] We estimated the anatomical labels according to the

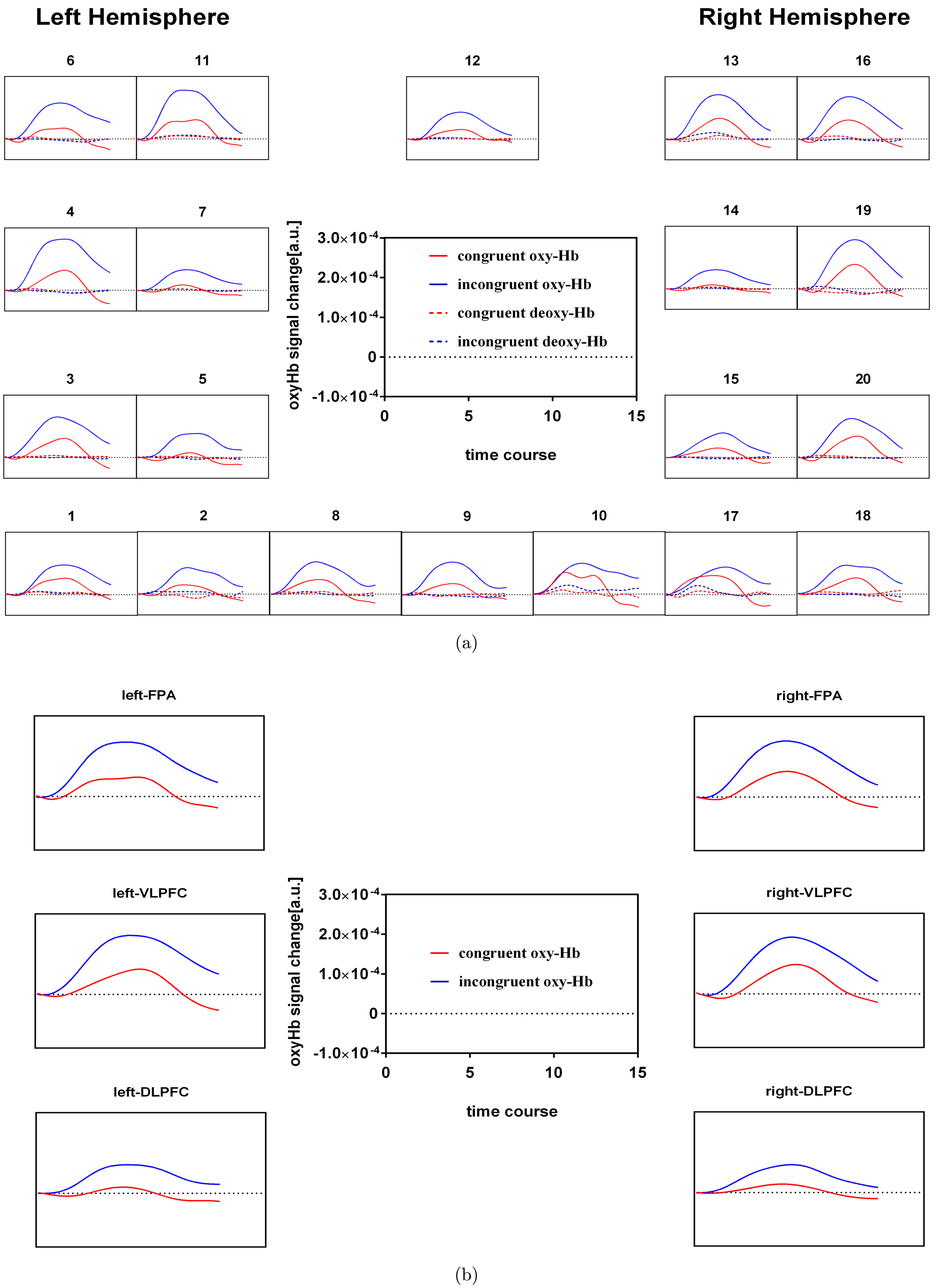


Fig. 2. Grand average time courses of oxy-Hb and deoxy-Hb to congruent (red) and incongruent (blue) condition at 20 channels (a). Grand average time courses of oxy-Hb to congruent (red) and incongruent (blue) condition at bilateral FPA, VLPFC and DLPFC (b).

Table 3. Relationship between BMI and hemodynamic data due to the Stroop effect.

	The overweight ($24 \leq$BMI <28)	The obese (BMI≥ 28)	
Brain region	Oxy-Hb interference (a.u.)	Oxy-Hb interference (a.u.)	t
l-FPA	0.000124 ± 0.000115	0.000023 ± 0.000081	2.904**
l-VLPFC	0.000118 ± 0.000120	0.000029 ± 0.000076	2.467*
l-DLPFC	0.000079 ± 0.000074	0.000005 ± 0.000065	3.002**
r-FPA	0.000078 ± 0.000102	0.000030 ± 0.000111	1.279
r-VLPFC	0.000089 ± 0.000105	0.000023 ± 0.000094	1.867
r-DLPFC	0.000068 ± 0.000066	0.000002 ± 0.000072	2.696*

Note: Oxy-Hb interference indicated the oxy-Hb difference between incongruent and congruent condition (the incongruent oxy-Hb minus the congruent oxy-Hb). Data are mean ± SD. *= $p < 0.05$; **= $p < 0.01$.

Table 4. Relationship between WC and hemodynamic data due to the Stroop effect.

	The non-central obese (WC $\leq$90 cm in males or $\leq$80 cm in females)	The central obese (WC $>$90 cm in males or $>$80 cm in females)	
Brain region	Oxy-Hb interference (a.u.)	Oxy-Hb interference (a.u.)	t
l-FPA	0.000131 ± 0.000112	0.000023 ± 0.000081	3.108**
l-VLPFC	0.000116 ± 0.000125	0.000036 ± 0.000078	2.186*
l-DLPFC	0.000081 ± 0.000074	0.000008 ± 0.000065	2.960**
r-FPA	0.000092 ± 0.000113	0.000021 ± 0.000094	1.913
r-VLPFC	0.000101 ± 0.000100	0.000015 ± 0.000092	2.504*
r-DLPFC	0.000064 ± 0.000069	0.000010 ± 0.000074	2.147*

Note: Oxy-Hb interference indicated the oxy-Hb difference between incongruent and congruent condition (the incongruent oxy-Hb minus the congruent oxy-Hb). Data are mean ± SD. *= $p < 0.05$; **= $p < 0.01$.

MNI coordinates of all the corresponding electrodes, and found that the activated channels were located above the bilateral FPA (CH6 and 11 for the left, CH13 and 16 for the right), bilateral DLPFC (CH5 and 7 for the left, CH14 and 15 for right) and bilateral VLPFC (CH3 and 4 for the left, CH19 and 20 for the right). Based on the concentration change of oxy-Hb during the Stroop task, we calculated the oxy-Hb interference in these brain regions.

Regarding BMI, the overweight subjects revealed a greater oxy-Hb interference than the obesity subjects in the left-FPA (l-, $t[31] = 2.904, p < 0.01$), l-VLPFC ($t[31] = 2.467$, $p < 0.05$), l-DLPFC ($t[31] = 3.002$, $p < 0.01$) and right-DLPFC (r-, $t[31] = 2.696$, $p < 0.05$) (Table 3). Regarding WC, the non-central obese subjects revealed a greater oxy-Hb interference than the central obese subjects in the l-FPA ($t[31] = 3.108$, $p < 0.01$), l-VLPFC ($t[31] = 2.186$, $p < 0.05$), l-DLPFC ($t[31] = 2.960$, $p < 0.01$), r-VLPFC ($t[31] = 2.504$, $p < 0.05$) and r-DLPFC ($t[31] = 2.147$, $p < 0.05$) (Table 4). Therefore, both obesity and central obesity were related to a decreased hemodynamic response during the Stroop task in the specific PFC regions.

4. Discussion

In the current study, we adopted fNIRS measurements to examine the underlying association between obesity markers and EF. BMI and WC, two anthropometric measurements, were closely linked to Stroop task performance.[34] Our finding suggests that both BMI and WC are similarly related to brain function and are negatively associated with the hemodynamic response in the PFC.

First, we examined the relationship between BMI and behavioral performance and observed that the subjects with a higher BMI demonstrated impaired behavioral performance compared to the subjects with a lower BMI. This finding replicates the findings of previous studies, which suggested an inverse relationship between BMI and behavioral performance on the Stroop task.[17] We also examined the relationship between WC and behavioral performance, which was seldom examined in the previous studies, and observed that subjects with central obesity demonstrated impaired behavioral performance. In a cross-sectional study of older adults, Waldstein and Katzel similarly suggested that central obesity predicted poor behavioral performance on the Stroop task.[35] In addition, Schwartz and colleagues suggested that there was a negative association between the Stroop interference and visceral fat, but not total body fat. Moreover, WC was found to be more closely connected to behavioral performance on a cognitive task than BMI in this adolescent-based study. Our findings and those from previous studies demonstrate that obese individuals have decreased behavioral performance during the Stroop task.

Based on behavioral results, we further examined the relationship between obesity and the hemodynamic data. In the present study, due to the Stroop effect, significant differences in oxy-Hb signals were observed in the FPA, VLPFC and DLPFC. This finding is generally consistent with the findings from previous neuroimaging studies, including those utilizing fNIRS.[17,31–33] One possibility is that the cognitive processes that mediate greater activation in the PFC are EF. Focusing on the color, rather than the semantic meaning, may require EF to inhibit our automatic or impulsive reactions, which in turn mediates greater brain activation on the incongruent trials compared to the congruent trials.[36,37] The involvement of specific PFC regions in EF could explain why obese individuals, who are considered to have difficulties resisting the temptation of food, had decreased activation in the DLPFC and VLPFC in response to food stimuli compared to normal-weight individuals.[20,34,38] Attention deficit hyperactivity disorder patients, who are believed to have impairments in EF, show decreased activation in the DLPFC and VLPFC during EF-related cognitive tasks compared to normal subjects. Both of these previous studies suggest that the PFC region might be involved in EF and inhibitory control.

In the present study, BMI was connected with activation in the PFC during the Stroop task. Obese compared to overweight young adults had less activation in the PFC regions including the l-FPA, l-VLPFC and bilateral DLPFC. Similarly, recent neuroimaging studies of obese and normal-weight individuals suggest that the obese has less activation in specific PFC regions during EF-related cognitive tasks, such as the go/no-go task and the stop-signal task. These studies did not investigate the relationship between central obesity and EF; therefore, the underlying mechanism of this association is largely unknown.[39,40] It is important to highlight that we observed the relationship between WC and brain function in young adults. Except for the obvious impact on health conditions, obese young adults face an increased risk of weight gain and cardiovascular disease later in life.[41,42] Along this line, accumulated obesity and interrupted physiological mechanisms might contribute to cognitive decline in the future.[43,44] In the present study, the central obese subjects revealed less brain activation due to the Stroop effect in the l-FPA, bilateral VLPFC and bilateral DLPFC compared to the non-central obese subjects. We observed that there was a significant difference in r-VLPFC activation between the high and low WC groups, which was not observed for BMI. This region is regarded as an inhibitory-related brain region and may be activated during response inhibition tasks, set-shifting tasks and memory retrieval inhibition. Moreover, the r-VLPFC is functionally and structurally connected to the presupplementary motor area, which is thought to be involved in the process of motor inhibition.[45–48] We might conclude that WC is negatively associated with EF and more closely connected to inhibitory control than BMI.

These findings may also reflect three potential consequences: (1) that central obesity causes sub-functioning EF; (2) that sub-functioning EF causes central obesity; or (3) that an independent factor causes both central obesity and sub-functioning EF. In the first consequence, central obesity enhances the effect of cardiovascular and metabolic risk factors on abnormal brain function, and in studies in rats and older adults, triglycerides and systemic inflammation would impair cognitive processes.[49–51] In this regard, central obesity influences the biological mechanisms that may lead to decreased cognitive function. Luchsinger and colleagues observed that central obesity is a reliable predictor of Alzheimer's disease.[52] In addition, Zeki Al Hazzouri *et al.* and Whitmer *et al.* suggested that central obesity increases the risk of cognitive decline in older adults.[53,54]

In the second consequence, an abnormal executive system is associated with obesity-related behaviors, whereas a well-functioning cortical executive system promotes goal-oriented behavior and contributes to the development of a positive healthy lifestyle.[55] According to the refined dynamic vulnerability model, Stice and Yokum hypothesized that individuals who have decreased activation in inhibitory regions during cognitive tasks might increase the risk of overeating and predict future weight gain.[56] In the present study, both obesity and central obesity subjects showed decreased hemodynamic responses during the Stroop test in the VLPFC and DLPFC. Activation in these regions might be related to inhibitory control.[38,57] Furthermore, the FPA might affect the cognitive control process. However, this region is a largely unknown human brain region[58]; therefore, we can conclude that less activation in specific PFC regions not only reflects poor inhibitory control but also reflects the increased risk of future weight gain among these obese subjects.

In the third consequence, lifestyle might correlate with obesity and EF. Food restriction and regular participation in sports have been proven to be successful body weight control strategies. Inversely, overeating and a sedentary lifestyle have been linked to future weight gain.[59] It has been discussed that sub-functioning EF might contribute to the development of negative lifestyle behaviors, particularly eating behaviors. Whether sub-functioning EF can predict an increased sedentary lifestyle is largely unknown. Recently, Hall *et al.* founded that abnormal r-DLPFC function hampered individuals from translating their exercise intentions into exercise behavior.[60] Alonso-Alonso and Pascual-Leone hypothesized that abnormal right-lateralized PFC function might weaken inhibitory control, which would lead to weight gain or obesity.[61] In the present study, the subjects with a relatively higher WC showed less hemodynamic responses during the Stroop task in the r-VLPFC and r-DLPFC. These findings might explain why it is difficult for individuals with central obesity to inhibit their unconscious impulses to be sedentary, which may have negative effects on cognitive development.[62] Accordingly, except for reducing energy intake and maintaining regular physical exercise, intervention programs that promote EF might also contribute to controlling body weight.[63]

As mentioned above, the large volume or thickness of the PFC was linked to higher executive performance; larger oxy-Hb interference in specific PFC regions reflects well-functioning EF. In the present study, we observed that a larger BMI and WC were associated with a relatively small oxy-Hb interference. Small oxy-Hb interference in specific PFC regions might represent relatively poor behavior and cognitive control. Therefore, we can conclude that both obesity and central obesity are associated with sub-functioning EF.

There are some limitations of the present study, such as the small number of subjects. In addition, the limited spatial resolution of fNIRS restricted our investigation in deeper brain regions such as the anterior cingulate cortex. Finally, the cross-sectional design of this study revealed the abnormal brain function of obese individuals; however, the influence of this abnormal brain function on lifestyle or future weight change is largely unknown.

5. Conclusion

In the present study, we used fNIRS to analyze the hemodynamic response during a Stroop task in individuals with obesity or central obesity. It has been shown that EF is restrained by obesity-related behaviors (e.g., overeating and a sedentary lifestyle), metabolic diseases and obesity itself.[64] The results from the present study reveal that obesity is associated with EF through behavioral and hemodynamic interference during the Stroop task in young adults. Both BMI and WC are indicators of EF. FNIRS is a reliable instrument to measure brain activation during the Stroop task in obese young adults.

Acknowledgments

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