Inquiro, the UAB undergraduate science research journal

Volume 2009 | Number 3 Article 35

2009

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Abstract

Obesity is a serious public health issue. Obesity may be accompanied by abnormalities in executive function circuitry related to inhibitory control or impulsivity. A useful task for studying impulsivity is the delay discounting (DD) of money task, in which an individual chooses between immediate and delayed, but greater, amounts of money. Selecting mostly immediate choices is related to increased impulsivity. Studies using functional magnetic resonance imaging (fMRI) have shown that difficult vs. easy choices on the DD task produce more activation in executive function circuitry. We report results of an fMRI study in obese women that examined modulation of executive function brain circuitry by trial difficulty. We hypothesized that obese women who were more impulsive on DD would show less activation of their executive function system on difficult choices compared to less impulsive obese women. Obese (Body Mass Index or BMI > 30) women (n = 60) first completed a standard version of a DD task on a PC in the lab. An individualized fMRI version of the DD task was made for each magnet-eligible participant (n = 21) such that half the trials were difficult and half were easy. The task was presented in an event-related design using a Siemens Allegra 3 Tesla head-only magnet. Task difficulty was analyzed based on relative number of immediate choices and on reaction time. Based on useful fMRI data obtained from 12 individuals, we found that obese women who made more impulsive choices on the DD task had less activation of executive function regions of the brain when making difficult vs. easy choices than women who showed less impulsivity. Our results suggest that impulsivity, a possible risk factor for obesity, may stem from hypoactivation of brain regions mediating executive functions. Knowledge of brain structures that are working less effectively in obese individuals could inform drug or behavioral treatments for obesity.

Introduction

The increasing prevalence of obesity and the fact that is a major contributing risk factor for a variety of illnesses has pushed the issue of obesity to the forefront of healthcare concerns, with the CDC ranking obesity as the number one health threat facing America (Mokdad, Marks, Stroup, & Gerberding, 2004). Obesity currently ranks as the second leading cause of preventable death in the United States, killing 400,000 individuals annually at a cost of $122.9 billion (Mokdad et al., 2004; NIH: National Institute of Diabetes, 2008). Given that obesity has a complex and multifaceted etiology, any research into potential risk factors for the development of obesity is important (Baskin, Ard, Franklin, & Allison, 2005; Ogden et al., 2006; Wyatt, Winters, & Dubbert, 2006). Suboptimal decision making, resulting in greater impulsivity, may be one of the risk factors for developing obesity.

Current neurobiological models have suggested that drug addiction is accompanied by abnormalities in the brain circuits involving the executive function system (Goldstein & Volkow, 2002; Jentsch & Taylor, 1999), specifically involving brain areas mediating decision making or impulsive behavior. In an addicted state, the saliency of the substance of abuse (alcohol, tobacco, or illicit substance) is able to overcome inhibitory control. Without this inhibitory effect to stop the drive to seek drugs, a positive feedback system is established, where consumption of the addictive substance leads to increased saliency, increased activation of the reward pathway, a larger subjective feeling of reward and finally the need to continuously consume the addictive substance (Volkow, Fowler, & Wang, 2004).

While this model is best applied to addiction, some obese people may display a similar decrease in effective use of executive circuitry to exert inhibitory control of their appetite (Volkow & Li, 2005; Volkow, Wang, Fowler, & Telang, 2008; Wang, Volkow, Thomas, & Fowler, 2004). Cognitive impairments have been found in obese as compared to healthy weight adults, specifically with regard to executive function and the decision making process (Cournot et al., 2006; Cserjési Luminet, Poncelet, & Lénárd, 2009; Elias, Elias, Sullivan, Wolf, & D'Agostino, 2003; Li, Dai, Jackson, & Zhang, 2008). While performing the Iowa Gambling Task, a useful task for assessing the decision making process, obese individuals or those with a higher Body Mass Index or BMI made more bad decisions than those with a lower BMI (Davis, Levitan, Muglia, Bewell, & Kennedy, 2004; Pignatti et al., 2006). Obese women have been shown to have deficits on a measure of inhibitory control, the Stop-Signal Task, and obese children tend to behave more impulsively than their normal-weight counterparts (Braet, Claus, Verbeken, & Van Vlierberghe, 2007; Nederkoorn, Braet, Van Eijs, Tanghe, & Jansen, 2006; Sigal & Adler, 1976).

Delay-discounting (DD), a particularly useful task for tapping into impulsivity (e.g., Reimers, Maylor, Stewart, & Chater, 2009), is the extent to which an individual will discount the value of a future reward as a function of the delay to it. The more distant a future reward is, the more its subjective value decreases in comparison to a smaller yet immediate reward. Initially, most people would choose a large amount of money over a small amount of money. However, if a delay to the larger amount of money is introduced and gradually increased; at some point some individuals

will prefer the smaller reward. The individual's subjective value of the larger amount of money has decreased with the introduction of a delay; an individual's indifference point is the point at which a larger, delayed reward and a smaller, immediate reward have the same subjective value for an individual (Bickel, Odum, & Madden, 1999; Kirby, Petry, & Bickel, 1999; Mazur, 1987).

A measure of DD is obtained by determining multiple indifference points, using them to plot a curve and from that extrapolating a single value (k). The hyperbolic function that is used to describe DD (Madden, Begotka, Raiff, & Kastern, 2003) is:

$$V = A / (1 + kD)$$

V is the present value of the delayed reward A at a delay of D and k is a free parameter that determines the discount rate. A higher k indicates a steeper slope of the hyperbolic curve and a higher rate of discounting. An individual with a high k discounts the future more steeply than one with a lower k and can be thought of as being more impulsive; thus k can also be considered as an impulsiveness parameter (Madden et al., 2003). Another way of characterizing DD is to plot subjective value vs. delay and determine the area under the curve, which has been suggested as a theoretically neutral measure of discounting (Myerson, Green, & Warusawitharana, 2001). While the DD task can be administered using a variety of rewards, money is used most often, sometimes with real monetary rewards (Johnson & Bickel, 2002).

Research has shown that there are established links between high alcohol consumption, smoking, opioid dependence, various other substance use disorders, gambling, having ADHD, and higher rates of DD (Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Bickel & Marsch, 2001; Bickel et al., 1999; Kirby et al., 1999; Madden, Petry, Badger, & Bickel, 1997; Mitchell, 1999; Monterosso, Ehrman, Napier, O'Brien, & Childress, 2001; Vuchinich & Simpson, 1998). For example, Vuchinich and Simpson (1998) found that college students who were identified as heavy drinkers had significantly higher discount rates, meaning that they were more impulsive, than light drinkers in hypothetical DD studies. Reynolds et al. (2004) found that adult smokers discounted more and were more impulsive than non-smokers. Kirby et al. (1999) found that heroin addicts discounted more steeply than control patients, and their discount rates were positively correlated with impulsivity. Previous research has also found that obese women display higher rates of impulsivity on the DD task than non-obese women, and that those with higher BMI's show greater impulsivity on a DD task (Reimers et al., 2009; Weller, Cook, Avsar, & Cox, 2008).

Executive function is usually attributed to areas including the prefrontal cortex (PFC), anterior cingulate cortex (ACC), superior parietal cortex (SPC), and inferior parietal cortex (IPC) (Gazzaniga, Ivry, & Mangun, 2002; Seeley et al., 2007). Several studies have been conducted to show a link between obesity and a deficit in these brain regions, as seen in those with substance abuse disorders (Volkow & Wise, 2005). Hypoactivation of the right PFC in obese individuals has been proposed as an explanation for overall poorer cognitive control of food intake (Alonso-Alonso & Pascual-Leone, 2007). Individuals with a high BMI are more likely to have smaller brain volumes and structural brain abnormalities in executive function areas such as the middle frontal gyrus (MFG) (Alkan et al., 2008; Gazdzinski, Kornak, Weiner, & Meyerhoff, 2008; Gunstad et al., 2008; Pannacciulli et al., 2006; Taki et al., 2007). As BMI increases, in otherwise healthy adults, a negative correlation between PFC and cingulate gyrus glucose metabolism emerges.

Functional Magnetic Resonance Imaging (fMRI) combines the high resolution anatomical images of an MRI with a way of indirectly measuring neural activity. Neural functional activity is measured using the "Blood Oxygen Level Dependent" (BOLD) effect, which correlates metabolic activity with neural activity. Activity in neurons causes increased blood flow which results in an increase in oxygenated (vs. deoxygenated) blood to the area of increased metabolic activity; the MRI scanner is able to detect deoxygenated blood due to its slightly magnetic nature. fMRI is a very useful neuroimaging tool due to its noninvasive nature and its very good spatial and fairly good temporal resolution.

Previous findings have established the validity of using fMRI analysis to examine the neural pathways that are involved in delay discounting and decision making. More difficult choices on the DD task produce greater brain activation in executive function structures in the prefrontal and parietal cortex than easier choices (McClure, Laibson, Lowenstein, & Cohen, 2004). Additional DD fMRI studies in those with a substance abuse disorder have suggested abnormal executive function activation when making difficult choices. Sober alcoholics showed reduced lateral orbitofrontal cortex (OFC) activation, whereas methamphetamine-dependent subjects showed lower activation in the ACC (Boettiger et al., 2007; Hoffman et al., 2008; Monterosso et al., 2007).

The present study is the first fMRI study of obese individuals using an executive function task. We hypothesized that obese women with higher impulsivity, as indexed by the DD parameter k, would show less activation of executive function circuitry during more difficult choices on the DD task than those with less impulsivity.

Methods

Participants

This research was approved by the UAB Institutional Review Board for Human Use. Participants were recruited using fliers posted around the UAB campus and in the *UAB Reporter*. Participants were obese (BMI > 30 kg/m^2) right-handed women between the ages of 18-50, without history of an addictive disorder or current use of psychoactive medication. Additional exclusionary criteria were being a cigarette smoker, pregnant or nursing, having a chronic health condition such as diabetes or past history of a serious medical condition, having a Shipley score < 85, show-

ing evidence of Axis I psychopathology or history of psychosis or active depression, having vision not correctable with contacts or the plastic eyeglass lenses available at the magnet (± 7 diopters), having ferromagnetic material in the body, history of loss of consciousness greater than 5 min., being claustrophobic, and exceeding the Siemens magnet bore (22.5" upper body width, 57-58" upper body girth) limits, which corresponded to weighing more than about 260 pounds.

Lab Session

Participants were screened in our lab prior to participating in the fMRI part of the study. While in the lab, participants had their height and weight measured to compute their BMI and completed questionnaires assessing IQ (estimated using the Shipley Institute of Living Scale, found to predict WAIS full scale IQ scores; Zachary, Paulson, & Gorsuch, 1985) and household income. Participants also completed an Eating Disorder Scale (EDDS) in order to screen for any eating disorders (Stice, Telch, & Rizvi, 2000).

A modified 27-choice version of the DD of money task (Kirby et al., 1999; Monterosso et al., 2007) was presented on a PC running Eprime v.1.2 software (Psychology Software Tools, Inc.). Choices were made using a button response pad similar to the one used in the magnet. The task consisted of 96 real choices (e.g., $20 now vs. $54 in 94 days) and 12 control choices (e.g., $0 now vs. $0 now). Control trials were needed to serve as sensorimotor controls for the fMRI version of the task, for future fMRI data analyses, and were given in the lab version simply to familiarize subjects with the procedure. The lab version of the task spanned a wide range of k's, in order to allow us to determine an individual k for each subject. Each trial was 11 sec. long, beginning with a fixation cross (+) presented for 2, 4, or 6 sec., followed by the two choices presented on the left or right side of the monitor (Fig. 1).

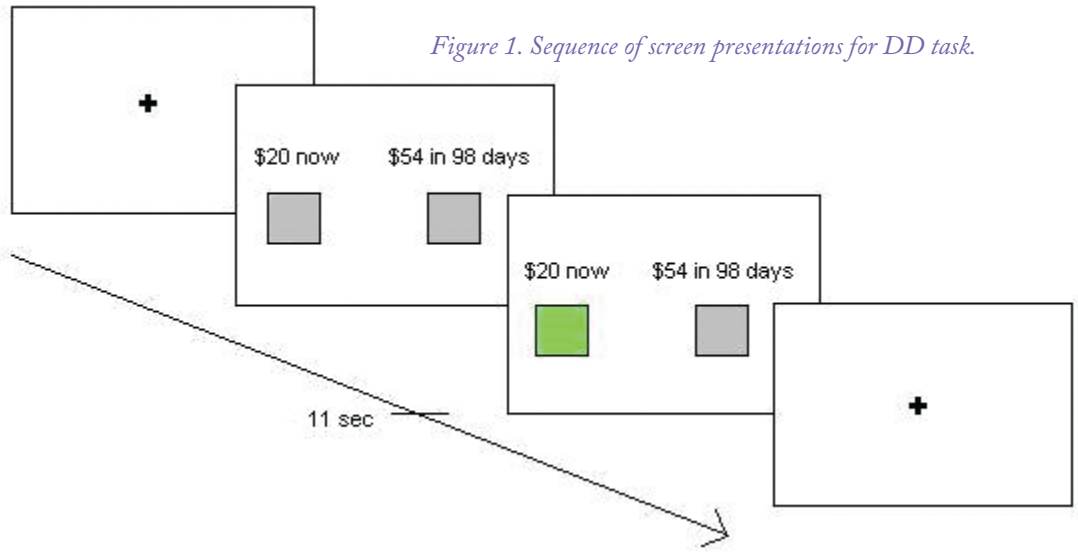


Figure 1. Sequence of screen presentations for DD task.

When the subject pushed the button for the left or right choice, the gray box under the choice turned green.

The DD task used was a real money task, and so, in addition to receiving money just for attending the lab session, each participant subsequently received half (lab session) or all (magnet session) of one of her choices , randomly selected, after the specified interval. Monetary choices ranged from $1 to $86, so the participant could receive between $.50 to $43 immediately or at a delay of 1 to 116 days (following procedures of Kable & Glimcher, 2007; McClure et al., 2004).

We used nonlinear regression to estimate each participant's k, with more impulsivity resulting in a higher k. This calculated k was then used to develop an individualized version of the DD task that would be used in the magnet session for that participant. Subjects were rejected if it became evident that they did not understand the task, were not paying attention, or resorted to using a rule to as opposed to assessing each trial independently during the lab session.

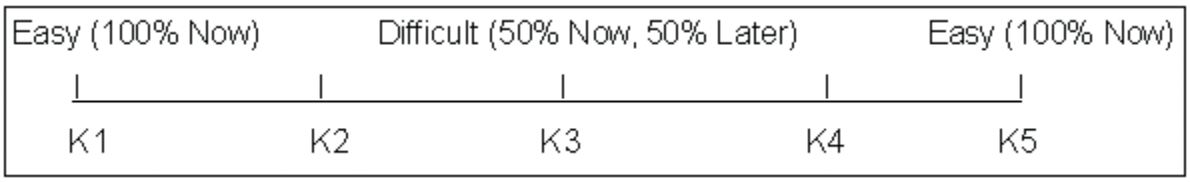
Magnet Session

Exclusionary criteria for participants subsequently used in the fMRI part of the study were that they did not make consistent choices during the DD lab task, their k was too low (> 0.002) or too high (< .05) for an individualized task to be developed for them, their Shipley IQ was < 85, or they had attributes that would prevent them from being safely scanned in the magnet. All women were scanned while in the follicular phase of their menstrual cycle.

An individualized version of the DD task was created for each participant's fMRI session consisting of 160 trials: 120 trials of five k categories and 40 control choices, divided into four blocks. The task was designed to ensure that there would be enough of each trial type; e.g., difficult, easy, immediate choice, later choice, for the fMRI data analysis. Across all of the available DD tasks, monetary amounts range from $0.37 - $78 for Now choices and from $29 - $86 for Later choices. Delays ranged from 1 - 116 days. The 120 real trials comprised five implied k (Imp-k) values. For all trials at a given Imp-k value, the Now and Later choices would have equal subjective values for a person whose value of k matched the Imp-k value (based on the equation Subjective Value = Later Value / [1+k*Delay]; Mazur, 1987). For each magnet participant, the Imp-k values spanned a range from well below to well above that person's lab k. The lowest and

highest Imp-k (K1 and K5) values represented trials intended to be easy for that person (large differences in subjective value between the Now and Later choices), and the intermediate Imp-k values (K2 and K4) represented trials intended to be more difficult (similar subjective values of the Now and Later choices). There was also a central Imp-k value (K3) that represented the most difficult trials (Fig 2).

Figure 2. Task difficulty on a k scale.



See text for details.

Task difficulty was measured using two measures: the percent of now choices when compared to later choices of equal subjective value (% Now), and reaction time or latency to button push. Some choices were easy, defined as being far from the subject's k, and others were difficult, defined as being close to the subject's k. The lowest and highest k categories represented easy trials, and the intermediate k categories represented difficult trials. Reaction time was defined as the period between the presentation of the two choices and the button push. A longer reaction time was considered an indication of a more difficult decision.

BOLD-fMRI data were collected from each participant using a Siemens Allegra 3 Tesla head-only magnet, IFIS visual display system, and MR-compatible response buttons. Functional MRI images were acquired using a single-shot T2*-weighted gradient-echo EPI pulse sequence. We used a TE of 30 ms, TR of 2.2 s, and a 70º flip angle for 30 axial-oblique slices 4 mm thick.

Obtaining useful data from a subject was dependent on her making consistent choices between her lab and magnet tasks and throughout her magnet task. If a subject's choices could be graphed and result in a hyperbolic curve with minimal interruption, then she was classified as consistent. If a participant appeared to have changed her level of impulsivity such that the individualized DD task was inappropriate for her (a "shifter"), then after the first block of trials, we paused the session and switched tasks, allowing us to choose a task that more accurately reflected the subject's k and would provide us with more useful choices. If a participant was later determined to have used a rule to answer all of the trials or was not paying attention, then her data were deemed unusable.

The fMRI data analysis was performed using the SPM5 software package (Wellcome Dept. Imaging Neuroscience, London, UK) run within Matlab (version 7.3; Mathworks, Inc.). Before the fMRI data could be analyzed, slice timing correction was applied as well as spatial preprocessing. The EPI images were first corrected for motion and then spatially transformed (normalized) into standard Montreal Neurological Institute (MNI) space, using a customized algorithm (Friston, Holmes, & Worsley, 1995). This transformation was then applied to the corresponding functional images, which were re-sliced into 2x2x2 mm resolution in MNI space. Finally, the images were spatially smoothed using a 6 mm FWHM Gaussian filter (Stoeckel, Weller, Cook III, Twieg, Knowlton, & Cox, 2008). Data sets in which movement before correction was greater than 2 mm in translational movement or 2˚ in rotational movement were excluded from analysis. The decision point used in the fMRI analysis for each trial was set at 500 ms before the button push.

fMRI data were analyzed using a Regions of Interest (ROI) approach, with ROI's being executive system structures that were expected to be activated more by difficult choices: gyral or lobular subdivisions of prefrontal (inferior frontal gyrus, middle frontal gyrus, superior frontal gyrus) and posterior parietal cortex (inferior parietal lobule, superior parietal lobule), anterior cingulate cortex, ACC, and lateral (Lat) orbitofrontal cortex (Boettiger et al., 2007; Hoffman et al., 2008; Monterosso et al., 2007). For the event-related analysis, trials were sorted into the k categories and these were used for the contrasts, Difficult > Easy choices. One analysis was used to validate that our DD task was tapping into executive function areas that were assumed to be more activated by greater mental effort. The other analysis was used to establish a correlation between executive function activation and impulsivity. Specifically, could we predict neural activation based on levels of k? Significance thresholds were $p < .001$, for the straight analysis of activation during difficult trials and $p < .05$ for the correlational analysis, with a minimum cluster size of 7 contiguous voxels.

A two-stage procedure was used for the statistical analysis of a mixed-effects design. At the first level, activation was computed for each individual subject on difficult > easy trials; difficulty was defined in terms of %Now, with trials closer to 50% now being more difficult, or in terms of reaction time (RT) activation, with longer reaction times being indicative of more difficult trials. For each voxel, SPM5 computed the contrast weights based upon the correlation between activation and reaction time. At the second level, these contrast weights were then entered into a random effects analysis to combine results at the group level. The correlation analysis was done using a conservative split-half analysis, in order to avoid strongly biased initial estimates of relationships between fMRI activation and log k (Vul, Harris, Winkielman, & Pashler, 2009; the log of k was used because the distribution of k was severely skewed, which is typical). First, areas of interest were defined based on negative correlations between difficulty-related

activity and ln k on half of the runs (e.g., runs 1 and 3). Then a standard correlation between log k and %Now activation was calculated to determine if a relationship existed between mean activity and impulsivity. Group data from runs 1 and 3 were used to identify a voxel within each ROI for which the difficult > easy contrast estimates showed the largest negative correlation with ln k. Using the MarsBar toolbox within SPM5, a sphere with a radius of 6 mm was constructed around the peak voxel within each ROI. The second level analysis of the correlation examined the difficult > easy contrast on runs 2 and 4, and then used MarsBar to calculate the average contrast estimate within each sphere for each subject. Correlations were then computed between these activations and ln k.

Results

Of the 21 participants run in the magnet, useful data using reaction time were obtained for n = 12 and for the %Now analysis, n = 10. Data from the other two participants were not used because of a lack of variability. Data from the other participants were not used either because these individuals were classified as "shifters" before correction procedures were implemented (n = 6), provided inconsistent responses that did not yield useful data (n = 1), appeared to use a shortcut or rule (n = 1), or had too much head movement (n = 1).

Table 1. Demographic Data

	Weight (lbs)	BMI (kg/m²)	Ethnicity
Magnet Session	197.38 ± 61.68	35.73 ± 3.97	5 AA (42%); 7 CA (58%)

n = 12, African American (AA), Caucasian American (CA).

Our first goal was to validate the use of our DD task by demonstrating that more difficult trials did produce greater brain activation in executive function areas, as had been found previously. We found that many executive brain areas did show greater activation on difficult vs. easy trials (Table 2). We also found that reaction time and %Now were convergent measures of task difficulty, in that analyses with both measures showed that more difficult choices produced greater activation in executive function brain areas than easy choices (Table 2). Reaction times for control trials, which served as sensorimotor controls, were on average one second. Reaction times for actual trials ranged from 2-4 seconds across subjects, with harder decisions have longer reaction times. We found greater activation on difficult choices as defined by %Now in the inferior (Inf.) frontal gyrus (Fig. 3A), Lat. OFC (Fig. 3B), middle (Mid.) frontal gyrus (Fig. 3C), anterior cingulate gyrus (Fig. 3D), and the inferior and superior parietal lobules. We found greater activation on difficult choices as defined by longer reaction times in the inferior and middle frontal gyri and the Lat. OFC.

Our other and main goal of the study was to show that level of impulsivity could predict executive system neural activation. Table 3 and Figures 4 and 5 shows brain areas that showed significantly less activation on difficult vs. easy trials, as defined by %Now and RT, associated with increasing impulsivity, presented as ln k, or a negative correlation (r). Higher k predicted less activation in the inferior and superior frontal gyri, anterior cingulate gyrus, and superior parietal lobule.

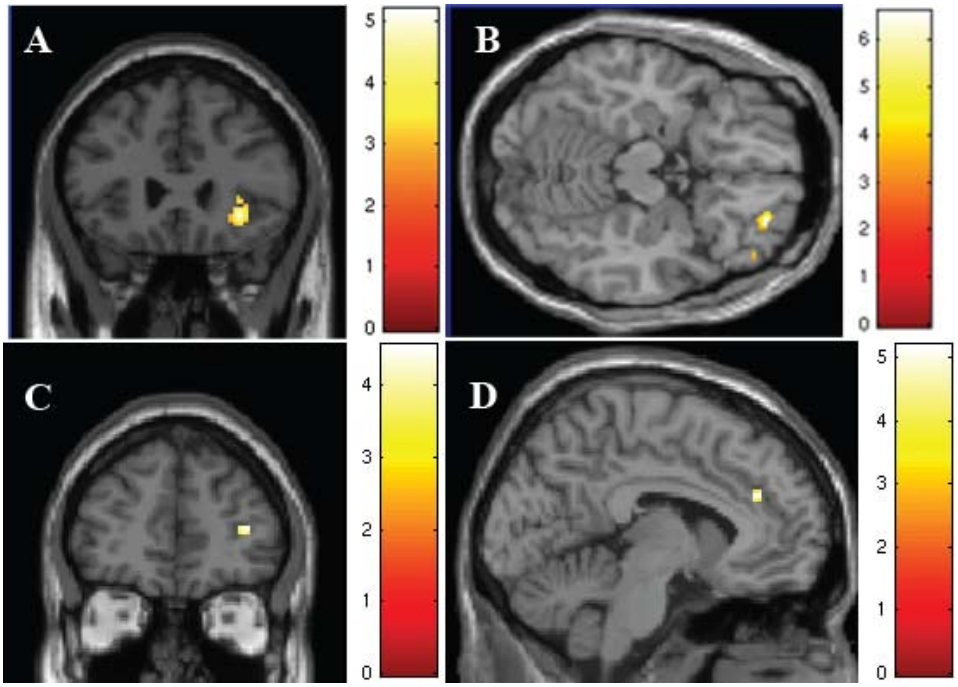


Figure 3 (left). Activation on difficult > easy contrasts.

(A) right inferior frontal gyrus, coronal view; (B) right lateral orbitofrontal cortex, axial view; (C) right middle frontal gyrus, coronal view; (D) left anterior cingulate cortex, sagittal view. Scale bar represents t-values.

Discussion

fMRI data collected to date from 12 obese women showed that our modified version of the delay-discounting of money task produced greater activation in executive function areas of the brain such as the inferior frontal gyrus and anterior cingulate cortex during difficult trials, compared to easier trials, mirroring the results of other comparable studies in normal or addicted individuals (Boettiger et al., 2007; Mc-

Difficulty Metric	ROI	Hem.	Cluster	t	x	y	z
% Now	Mid. Frontal Gyrus	L	7	4.17	-24	30	38
		R	11	4.55	38	46	10
	Lat. Orbitofrontal Cortex	L	22	4.81	-36	32	-8
		R	29	6.59	28	48	-16
	Ant. Cingulate Gyrus	L	9	5.2	-6	38	26
		R	7	4.08	14	22	28
	Inf. Parietal Lobule	L	16	5.84	-56	-38	36
		R	8	8.69	48	-30	32
	Sup. Parietal Lobule	L	7	4.27	-24	-74	46
		R	11	5.03	20	-72	44
RT	Inf. Frontal Gyrus	L	31	4.69	-32	20	-4
		R	83	5.5	32	26	-6
	Mid. Frontal Gyrus	L	15	4.73	-48	18	36
	Lat. Orbitofrontal Cortex	L	18	7.47	-40	48	-14

Table 2. ROIs with significantly greater activation on difficult > easy contrasts as defined by %Now and RT.

ROI, region of interest; Hem., hemisphere; x, y and z, Montreal Neurological Institute coordinates relative to the anterior commissure (AC) or AC-PC (posterior c) line; Inf., inferior; Med., medial; Sup., superior; Ant., Anterior; Lat., lateral. p <.001, at least 7 contiguous voxels. T- values based on t-tests

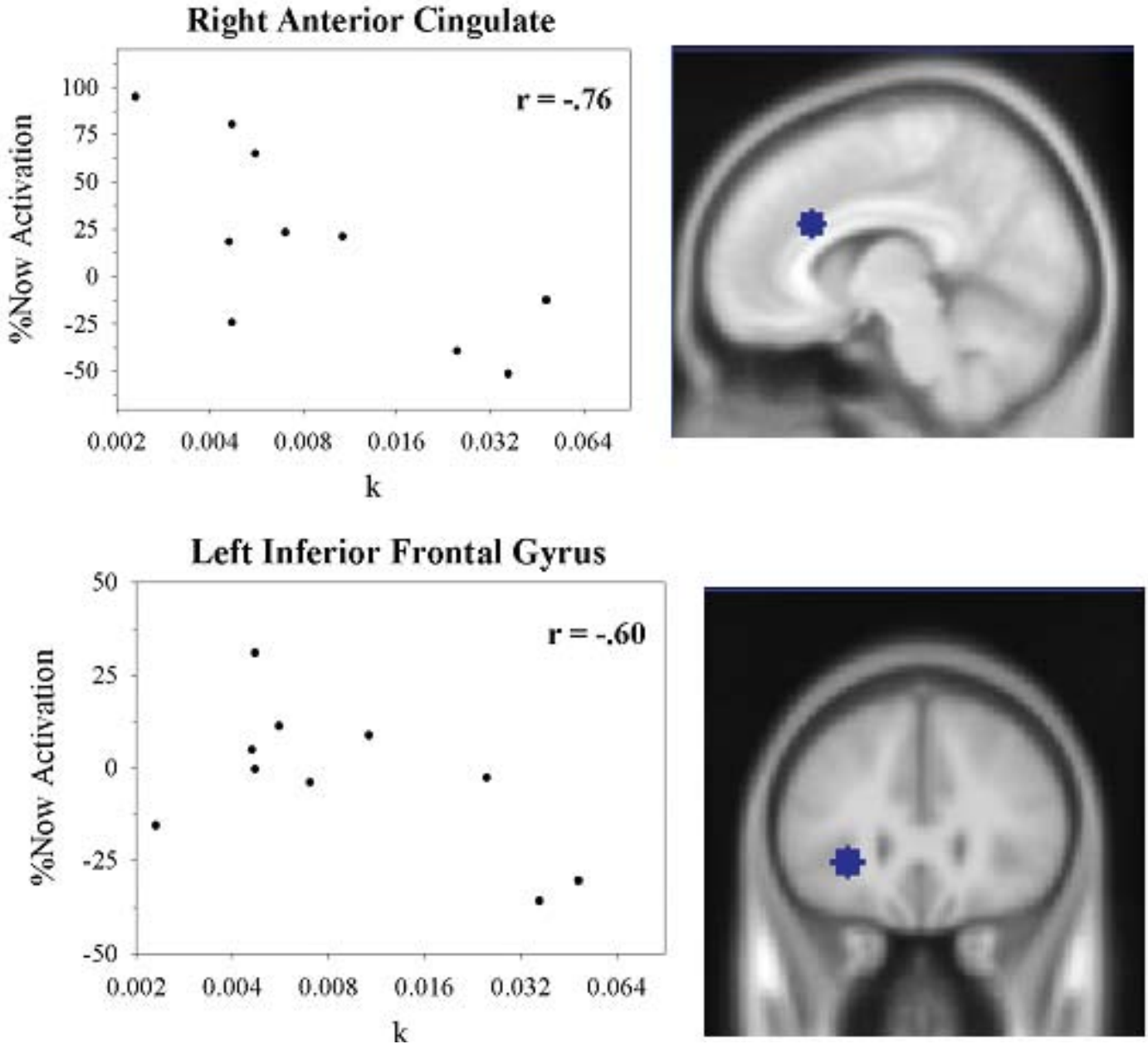
Difficulty Metric	ROI	Hem.	r	x	y	z
%Now	Inf. Frontal Gyrus	L	-0.59	-30	28	-2
	Sup. Frontal Gyrus	R	-0.56	28	46	30
	Ant. Cingulate Gyrus	R	-0.76	8	24	26
RT	Sup. Parietal Lobule	R	-0.59	24	-78	40

Conventions as in Table 1.

Table 3. ROIs with a significant correlation between task difficulty and impulsivity, difficult > easy vs. ln (k).

Conventions as in Table 2. Correlations computed using a split half analysis. p < .05, at least 7 contiguous voxels.

Figure 4. Difficult > easy contrast estimates plotted vs. k on a log scale and the corresponding brain ROI.

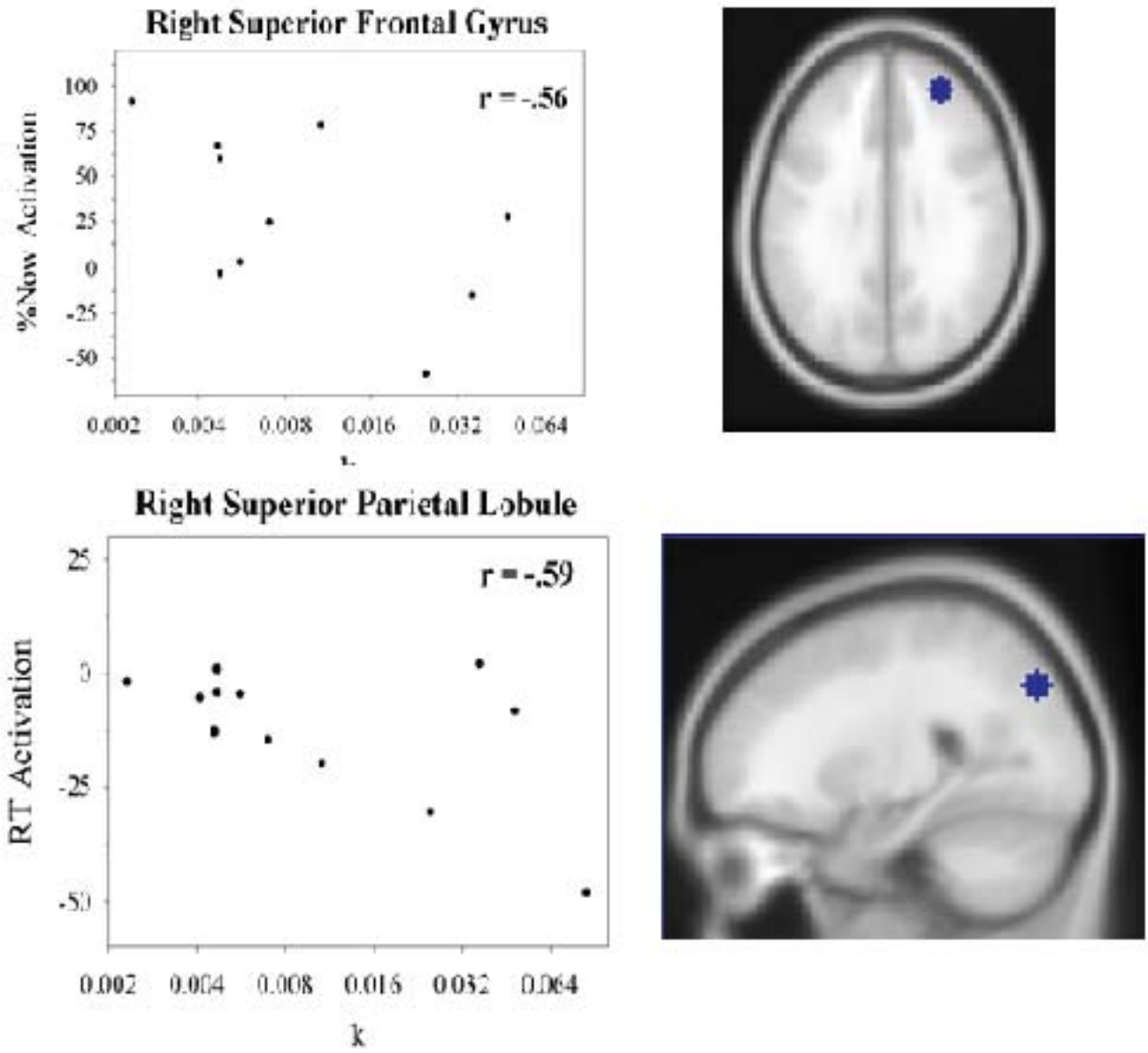


The graphs on the left illustrate the relationship or correlation between impulsivity (ln k) and activation on difficult vs. easy trials as defined by %Now for the brain ROI indicated, with the corresponding MR images on the right highlighting the MarsBar-created ROI used for the split-half analysis. Top right, sagittal view; bottom right, coronal view.

Clure et al., 2004; Monterosso et al., 2001). The two measures of task difficulty, reaction time and %Now, provided convergent results with regard to executive function activation. As a reminder, the delayed-discounting task has been shown to tap into impulsivity, and other research has established the relationship between greater impulsivity on the delayed-discounting task and higher BMI (Reimers et al., 2009; Weller et al., 2008). We also found, as hypothesized, greater impulsivity in obese women, as assessed by the discount parameter k on the delay-discounting task, was associated with less activation in executive system regions during difficult vs. easy choices.

Efficient executive control involves many processes, including planning, monitoring and correcting errors, multitasking, deciding between alternatives, and inhibition (Gazzaniga et al., 2002). A restatement of our results about deciding between alternatives, perhaps by using inhibitory control, is that less impulsive obese women showed greater activation of executive function cortex

Figure 5. Difficult > easy contrast estimates plotted vs. k on a log scale and the corresponding brain ROI.



Conventions as in Figure 4, except that the top right MarsBar-created ROI is shown on an axial view and the bottom ROI on a sagittal view.

during difficult vs. easy trials. One implication of this result is that self control utilizes executive function neural circuitry to a greater extent than does "giving in". This is exactly the result found in a recent fMRI study by Hare and colleagues (Hare, Camerer, & Rangel, 2009), who studied dieters or "self-controllers" vs. "non-self-controllers". When the self-controllers had to decide between choosing (for later consumption) tasty but unhealthy foods or neutral foods, they had greater activation in dorsolateral pre-frontal cortex, in particular, the left inferior frontal gyrus, during successful than failed self-control trials. The IFG was one of the ROI's we found to be less activated during difficult trials in the more impulsive obese women.

Inhibition is crucial in human behavioral control since it allows us to suppress automatic, impulsive, or routine behavior, and therefore avoid errors. However, when an error is made, detecting that error helps us to adapt our behavior appropriately so as to avoid further errors (Simões-Franklin, Hester, Shpaner, Foxe, & Garavan, 2009). The inferior frontal gyrus (IFG) has been implicated in inhibitory control, and is especially activated under conditions

of increased response competition. While some studies have suggested that it is mainly involved in inhibition of motor responses, others have shown that the IFG is also involved in non-motor inhibition and serves as a general purpose inhibition mechanism (Chambers et al., 2007; Swick, Ashley, & Turken, 2008). This is consistent with our findings of decreased activation in the right IFG during difficult vs. easy trials correlated with increased impulsiveness.

Another of the key areas associated with executive function is the anterior cingulate cortex (ACC). Amongst its many suggested roles, the anterior cingulate functions in inhibitory control over motivation (Allman, Hakeem, & Watson, 2002). It helps an individual recognize an error committed and to adapt and reduce future errors. Our results showed that difficult vs. easy trials produced greater activation of the left ACC, and increased impulsiveness was correlated with decreased activation in the left ACC during difficult trials.

Less efficient use of executive system regions may lead to decisions being driven more by other systems (i.e., reward), resulting in relatively more choices for immediate compared to delayed rewards, or more impulsive choices. Within the context of obesity, if executive function areas are functioning less efficiently, this could have a significant impact on diet and lifestyle choices, thereby increasing the risk of obesity. Knowledge of brain structures that are working less effectively in obese individuals could inform drug or behavioral treatments for obesity.

Acknowledgements
I would like to thank Kathy Avsar for making the button response pad used for the DD lab task, Luke Stoeckel and Matt Eddinger for helping run subjects in the lab and magnet sessions, Donna Murdaugh for running subjects and data analysis, Dr. Jim Cox, and the Civitan International Research Center for use of their facility and equipment. Support provided by a UAB/NSF ADVANCE grant to R. Weller and GCRC Grant #M01-RR00032.

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