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Psychological Science published online 5 September 2014
DOI: 10.1177/0956797614546001

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http://pss.sagepub.com/content/early/2014/09/04/0956797614546001

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What is This?
Curbing Craving: Behavioral and Brain Evidence That Children Regulate Craving When Instructed to Do So but Have Higher Baseline Craving Than Adults

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Abstract
Although one third of children and adolescents are overweight or obese, developmental changes in food craving and the ability to regulate craving remain poorly understood. We addressed this knowledge gap by examining behavioral and neural responses to images of appetizing unhealthy foods in individuals ages 6 through 23 years. On close trials (assessing unregulated craving), participants focused on a pictured food's appetitive features. On far trials (assessing effortful regulation), participants focused on a food's visual features and imagined that it was farther away. Across conditions, older age predicted less craving, less striatal recruitment, greater prefrontal activity, and stronger frontostriatal coupling. When effortfully regulating their responses to the images, all participants reported less craving and exhibited greater recruitment of lateral prefrontal cortex and less recruitment of ventromedial prefrontal cortex. Greater body mass predicted less regulation-related prefrontal activity, particularly among children. These results suggest that children experience stronger craving than adults but can also effectively regulate craving. Moreover, the mechanisms underlying regulation may differ for heavy and lean children.

Keywords
childhood development, neuroimaging, adolescent development, food, emotional control

Received 3/20/14; Revision accepted 7/11/14

Today, one third of youth in the United States are overweight or obese (Ogden, Carroll, Kit, & Flegal, 2012). This is troubling, given that childhood obesity predicts adult obesity and long-term health problems. These observations have led some researchers to characterize childhood and adolescence as sensitive periods for the acquisition of obesity (Dietz, 1994). Thus, this developmental window is an ideal target for early intervention aimed at preventing weight gain. Although prior work indicates that children's reward sensitivity (Verbeken, Braet, Lammertyn, Goossens, & Moens, 2012) and self-regulatory ability (Batterink, Yokum, & Stice, 2010; Francis & Susman, 2009; Schlam, Wilson, Shoda, Mischel, & Ayduk, 2013) are associated with their concurrent and future body mass index (BMI), little is known about how food craving, its regulation, or its association with BMI relates to age. Using neuroimaging and behavioral methods, the present study addresses three questions about food craving in children, adolescents, and adults.

The first question is whether food craving differs as a function of age. Numerous studies have shown that impulse control improves from childhood to adulthood,
but may be compromised in certain contexts in adolescence (Somerville & Casey, 2010). Relative to adults, adolescents perform better on cognitive and decision-making tasks when incentives are at stake (Geier, Terwilliger, Teslovich, Velanova, & Luna, 2010; Teslovich et al., 2014), yet also impulsively approach positive stimuli (Somerville, Hare, & Casey, 2011). This tendency for motivational factors to modulate cognitive control has been linked to exaggerated responses in reward regions like the ventral striatum (VS; Galvan et al., 2006; Van Leijenhorst et al., 2010).

To date, two neuroimaging studies have compared how adolescents and adults respond to food. In the first study, participants were given juice to drink; compared with adults, adolescents showed heightened VS responses and reported enjoying the juice more (Galván & McGlennen, 2013). In the second study, participants viewed food images; no age effects in the VS were observed, and on-line self-reports were not collected (Killgore & Yurgelun-Todd, 2005). These mixed findings make it unclear whether adolescents are more responsive to food than adults are. In addition, given that participants under the age of 9 were not tested in either study, it remains unclear how adolescents and adults differ from children in their responses to food.

The second question is whether age predicts general changes in food craving or, specifically, the capacity to regulate craving using cognitive strategies such as reappraisal, which involves thinking about a stimulus differently so as to alter its affective impact. In adults, reappraising food reduces craving (Giuliani, Mann, Tomiyama, & Berkman, 2014; Kober et al., 2010; Siep et al., 2012; Wang et al., 2009); recruits dorsolateral, ventrolateral, and dorsomedial prefrontal regions (dIPFC, vlPFC, and dmPFC, respectively) implicated in cognitive control (Giuliani et al., 2014; Kober et al., 2010; Scharmüller, Übel, Ebner, & Schienle, 2012), and attenuates activation of reward-related circuitry (Kober et al., 2010; Wang et al., 2009), including the VS and ventromedial prefrontal cortex (vmPFC). One prior neuroimaging study of adolescents found that reappraising food recruited vlPFC, but did not reduce craving or vmPFC or VS activation (Yokum & Stice, 2013). The mixed results of this latter study make it unclear whether youth can reappraise food and, given that no adults were scanned, leave open the question of whether age predicts differences in the ability to regulate craving.

Our third question concerns the extent to which BMI is associated with behavioral and neural responses to food in youth. Obese and overweight adults report more food craving in everyday life than lean adults do (Delahanty, Meigs, Hayden, Williamson, & Nathan, 2002), and greater body mass predicts heightened VS activity (Giuliani et al., 2014) and reduced lateral prefrontal recruitment both when responding to food naturally (Brooks, Cedernaes, & Schioth, 2013) and when regulating food craving (Giuliani et al., 2014). It is unknown, however, how BMI relates to food craving and its regulation in childhood and adolescence.

To address these three questions, we scanned participants ages 6 through 23 years while they viewed appetizing unhealthy foods and alternately focused more (baseline trials) or less (craving-regulation trials) on the food's appetitive features. To test whether age predicts general changes in responsivity to food, we examined developmental differences with regard to self-reported craving and frontostriatal activity across these two experimental conditions. To test whether the ability to cognitively regulate craving increases with age, we compared age effects between regulation and baseline trials. Finally, we examined the influence of age-adjusted BMI (i.e., BMI percentile) on food craving and neural responses.

**Method**

**Participants**

One hundred five healthy individuals 6 to 23 years of age participated in the experiment (71 female; mean age = 14.27 years, SD = 4.85; for additional details, see Fig. S1 in the Supplemental Material available online). Participants were prescreened prior to participation to ensure that they could read and write in English, had normal or corrected vision, had never been diagnosed with a developmental or psychiatric disorder, had no conditions that contraindicated scanning, and had never been prescribed psychotropic medication. All participants were of normal intelligence (M = 114.57, SD = 15.93) as indexed by the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999), and no relationship between age and IQ score was observed (r = –.08, p > .05). A subset of participants (n = 45; 25 female; mean age = 17.71 years, SD = 3.59 years) completed the SCOFF questionnaire, a screen for eating disorders (Morgan, Reid, & Lacey, 2000). SCOFF scores did not correlate with age or with craving in either experimental condition (ps > .10), which suggests that age-related changes in craving were not attributable to restrained or disordered eating.

In addition to the 105 participants whose data are presented in this report, 10 participants (6 female; mean age = 8.36 years, SD = 1.92) were scanned but excluded from analyses because of excessive head motion. The target sample size was initially set at 100 participants, but 115 people were scanned because it was anticipated that some data might need to be excluded because of head motion. The Columbia University Institutional Review Board approved this study, and participants provided informed consent and (in the case of minors) assent.
Participants were not given explicit instructions regarding fasting prior to scanning. A subset of participants (n = 57) were asked about the last time they ate before scanning, and time since eating was unrelated to craving in both experimental conditions, as well as to the difference in craving between the conditions (p > .20). Because of feasibility constraints, participants were scanned at different times of day: 15.2% in the morning (8:30–11:59 a.m.), 55.2% in the afternoon (12:00–4:59 p.m.), and 29.5% in the evening (5:00–7:30 p.m.). Time of day did not predict craving in either experimental condition, nor did it interact with condition or age to predict craving (p > .27).

After scanning, participants were weighed, and their height was measured. Prior work has suggested that BMI percentile (i.e., BMI relative to same-age peers) is a more accurate assessment of body composition than is BMI for children and adolescents (Mei et al., 2002). The Center for Disease Control’s BMI-for-age growth chart (Kuczmarski et al., 2000) was used to calculate BMI percentile. Because data on BMI percentile are not published for individuals over the age of 20, 17 participants ages 20 to 23 were not included in analyses examining BMI. Thus, 86 individuals (53 female; mean age = 13.71 years, SD = 4.04) were included in our BMI analyses. Neither age nor gender was associated with BMI percentile (p > .32).

**Experimental task**

Participants completed a regulation-of-craving task consisting of 40 experimental trials, all of which involved the presentation of a picture of unhealthy but appetizing food (Fig. 1a). Food stimuli were downloaded from public online sources. Care was taken to present participants with a variety of types of food stimuli (e.g., equivalent representation of salty and sweet foods). Pilot testing in a prior sample of children, teenagers, and adults confirmed that all the foods depicted were highly desirable.

Each experimental trial began with the presentation of a cue word ("Close" or "Far," shown for 2 s). Participants implemented the strategy indicated while viewing the following food stimulus for 8 s. After a jittered fixation period (~3 s), participants used a 5-point scale to rate, via button press, how much they wanted to eat the food they
had just seen (1 = not at all, 5 = very much). The trial concluded with a second jittered fixation period (~3 s).

Half of the trials were in the close condition, and half were in the far condition. Assignment of pictures to conditions was counterbalanced across participants. Prior to the task, participants were trained on the strategies to be used in these conditions, in accordance with procedures that have been well validated in developmental populations (Silvers et al., 2012). Participants were told that on close trials, they should imagine that the food was in front of them and should focus on the taste and smell of the food. They were told that on far trials, they should imagine that the food was farther away and should focus more on the visual aspects of the food (e.g., the shape and color) than on its appetitive features. Participants were not told that close trials were intended to assess baseline appetitive responsiveness whereas far trials were intended to assess regulation.

**Scanning**

Whole-brain functional MRI (fMRI) data were acquired on a 3-T Siemens Magnetom Trio scanner. Structural images were acquired using a high-resolution, T1-weighted magnetization-prepared rapid-acquisition gradient echo (MPRAGE) sequence, with a repetition time (TR) of 2,170 ms, an echo time (TE) of 4.33 ms, and 120 1.5-mm slices. Functional images were acquired with a T2*-sensitive echo planar imaging (EPI) blood-oxygen-level dependent (BOLD) sequence. Thirty-four axial slices were collected with a TR of 2,000 ms (TE = 34 ms, flip angle = 90°, field of view = 22.4 cm, 3.5- × 3.5- × 4-mm voxels). Stimuli were presented using E-Prime 1.0 (Psychology Software Tools, Inc., http://www.pstnet.com) and were projected onto a flat screen mounted in the scanner bore. Participants viewed the screen using a mirror mounted on a 16-channel head coil. They made their responses using a five-finger button response pad.

**Behavioral data analysis**

Effects of condition (close, far), mean-centered age, and BMI percentile on self-reported craving were analyzed using a repeated measures general linear model (GLM), as implemented in SPSS 19.0.

**fMRI analysis**

Preprocessing was conducted using SPM8 (Wellcome Department of Cognitive Neurology, Institute of Neurology, London, England). Preprocessing steps consisted of slice time correction, realignment, and coregistration of the functional and structural data. Images were segmented and normalized (warped) to the standard Montreal Neurological Institute (MNI) template brain. Normalized functional images were interpolated to 3- × 3- × 3-mm voxels and spatially smoothed with a 6-mm Gaussian filter. A gray-matter mask based on the MNI-standardized Colin brain was used to constrain the functional data.

Prior to scanning, children under the age of 10 were acclimated to the scanning environment with the use of a mock scanner so as to enhance their comfort and give them an opportunity to practice staying still. After scanning, motion parameters were estimated during preprocessing, and volumes that contained motion greater than 1.5 mm (translation) or 2° (rotation) relative to the preceding volume were excluded from further analyses. If 10% or more of the volumes from a given run were excluded, the entire run was discarded. Participants were excluded if more than two of the four runs were discarded. Activation values from clusters identified in age-related analyses were tested off-line while controlling for the number of volumes removed to examine whether age effects still held. These adjusted age effects are reported in Tables S1, S2, S3, S5, and S8 in the Supplemental Material.

First-level GLM analyses were implemented in NeuroElf (http://neuroelf.net). Cue, stimulus-viewing, and response portions of each trial were modeled as boxcar regressors convolved with a canonical hemodynamic response function. Separate regressors were made for the stimulus-viewing period of close and far trials. Robust regression was used in first-level analyses. Motion parameters, a high-pass temporal filter, and estimates of global signal in white matter, gray matter, and cerebrospinal fluid were included as regressors of no interest. We calculated temporal signal-to-noise ratios (tSNRs) for each participant’s neuroimaging data by taking the mean value of each voxel’s time-series intensity and dividing it by the standard deviation of the voxel’s time-series intensity (Welsaert & Rosseel, 2013). Age was not correlated with tSNR, $r = −.03$, $p = .78$, an indication that age did not predict significant differences in data quality.

Following GLM computation for each participant, second-level random-effects analyses were performed on the group data. The first analysis examined the effects of condition (close, far) and mean-centered age, and the second examined the effects of condition, mean-centered age, and mean-centered BMI percentile. Both linear and quadratic effects of age were examined, and these analyses identified nearly identical clusters in the brain. To determine model fit, we performed conjunction analyses to isolate clusters identified by both the linear and quadratic models. Parameter estimates were then extracted from these clusters and examined off-line using extra sum-of-squares $F$ tests. Significant main effects and interactions were examined with follow-up $t$ tests and correlational analyses to ascertain the directionality of effects. Significant
clusters were identified using joint voxel and extent thresholds that preserved an alpha of less than .05, as determined by AlphaSim (1,000 iterations; smoothness estimated at 10.6 mm by AlphaSim), implemented in NeuroElf (uncorrected $p < .005$ and 79 voxels).

To examine age-related changes associated with VS connectivity, we also conducted a psychophysiological interaction (PPI) analysis. The seed region used was the right VS cluster identified by the main-effect-of-age term in the activation-based analyses just described (MNI coordinates: 18, 12, −6). In this analysis, regressors were created for each experimental condition, the seed-region time series, and interaction terms for the seed-region time series and the two experimental conditions (i.e., Close × PPI and Far × PPI). Given that this VS seed region was identified by the main effect of age in the activation-based analyses (i.e., the effect of age collapsed across close and far trials), the primary test in this analysis concerned whether the effect of age across the two experimental conditions was greater than the effect of age during fixation (Close × PPI + Far × PPI > fixation). Follow-up regression analyses were conducted on the clusters identified in this analysis to determine whether age predicted comparable changes in connectivity for the close and far conditions. In addition, whole-brain tests were performed to identify clusters that showed age-related variation in task-independent connectivity (i.e., connectivity predicted by the VS seed’s time course) and overall connectivity during the task (task-independent connectivity + task-dependent connectivity) and are reported in the Supplemental Results and Table S3 in the Supplemental Material. Significant clusters were identified using a joint voxel and extent threshold that preserved an alpha of less than .05, as determined by AlphaSim (1,000 iterations; smoothness estimated at 9.3 mm by AlphaSim), implemented in NeuroElf (uncorrected $p < .005$ and 56 voxels).

**Results**

**Behavioral results**

To characterize developmental differences associated with food craving, we computed the main effect of age on self-reported craving (Fig. 1b). Results revealed that older individuals reported less craving than younger individuals, $F(1, 103) = 12.09, p < .001, \eta^2_p = .13$. Adding a quadratic age term (age$^2$) did not improve model fit, as determined by the extra sum-of-squares $F$ test, $F(1, 102) = 0.12, p = .73$, and thus the simpler linear model of age was used. To examine whether reappraisal reduced craving regardless of age, we tested the main effect of condition. As expected, participants reported less craving on far than on close trials, $F(1, 103) = 68.29, p < .001, \eta^2_p = .40$. Age effects were not unique to the far (reappraisal) condition, as there was no interaction between age and condition, $F(1, 105) = 0.86, p = .36, \eta^2_p = .008$. Participants of different ages used the craving scale similarly, as evidenced by the fact that age did not predict differences in within-subject standard deviations for craving ratings (mean $SD = 1.22, r = −.08, p = .40$. Age-adjusted BMI did not predict craving, nor did the interaction term between BMI and condition ($ps > .29$). Even when the top and bottom quartiles for BMI were examined separately, no differences in craving were identified for either condition ($ps > .71$).

**Imaging results**

**Main effects of age.** Older age predicted increased recruitment of right lateral prefrontal and bilateral posterior parietal cortices and decreased recruitment of subcortical structures implicated in reward and emotional processing, such as the VS (Liu, Hairston, Schrier, & Fan, 2011) and amygdala (Buhle et al., 2013), during presentation of food pictures relative to fixation (Fig. 2a; see also Table S1 in the Supplemental Material). Similar regions of interest (ROIs) were identified by linear and quadratic models of age, but the more complex quadratic model did not improve model fit relative to the simpler linear model in any regions ($p > .09$).

To further investigate age effects observed in the VS, we conducted a PPI analysis using the VS as a seed region (MNI coordinates: 18, 12, −6). Task-independent connectivity (i.e., connectivity predicted by the VS seed’s time course alone) in the vmPFC was positive regardless of participants’ age (see the Supplemental Results in the Supplemental Material). Older age predicted more positive task-related vmPFC-VS connectivity during close trials (vmPFC-VS coupling for close > fixation = −.27 + .017 $\times$ age) and far trials (vmPFC-VS coupling for far > fixation = −.39 + .025 $\times$ age) relative to fixation (Fig. 2b; see also Table S2 in the Supplemental Material). Age effects on vmPFC-VS functional connectivity did not differ significantly between close and far trials ($p > .14$). Greater task-related increases in vmPFC-VS coupling predicted less craving, $\beta = −.65, t(103) = 2.13, p < .05$, but not after controlling for age, $\beta = −.24, t(103) = 0.76, p = .45$. Older age continued to predict less craving after controlling for vmPFC-VS connectivity, $\beta = −.05, t(103) = 4.32, p < .005$.

Age also predicted task-related VS connectivity with the supplementary motor area (SMA) and the central sulcus (CS). As was the case with vmPFC-VS connectivity, age-related effects on SMA-VS and CS-VS connectivity did not differ between close and far trials ($ps > .42$; see also Table S2 in the Supplemental Material). Task-independent connectivity (i.e., connectivity predicted by the VS time course) between the VS and the SMA (Fig. 2b) and
between the VS and the CS was negative (see Supplemental Results in the Supplemental Material for details). SMA-VS and CS-VS connectivity became stronger during the task relative to fixation during early to mid adolescence (SMA-VS coupling for close trials > fixation = 0.19 − 0.014 × age; SMA-VS coupling for far trials > fixation = 0.20 − 0.014 × age; CS-VS coupling for close trials > fixation = 0.19 − 0.014 × age; CS-VS coupling for far trials > fixation = 0.22 − 0.017 × age; Table S2). Stronger (i.e., more negative) coupling during the task compared with fixation predicted less craving across close and far trials in the case of both SMA-VS coupling, $\beta = 1.48$, $t(103) = 3.05$, $p < .005$, and CS-VS coupling, $\beta = 0.87$, $t(103) = 2.39$, $p < .05$, but not after controlling for age ($p$s > .15).

**Main effects of condition and interactions between age and condition.** Regulation of craving was associated with robust recruitment of left vlPFC, bilateral dlPFC, bilateral dmPFC, and bilateral posterior parietal cortex (i.e., far > close contrast) regardless of participants’ age (Fig. 3; see also Table S4 in the Supplemental Material). Regulation of craving attenuated activation of vmPFC as well as the cuneus and fusiform gyrus (i.e., close > far contrast; Fig. 3). Age and condition interacted to predict recruitment of the putamen (see Table S5 in the Supplemental Material). Linear and quadratic models of age identified similar ROIs, but the more complex quadratic model did not improve model fit relative to the simpler linear model in any region ($p$s > .2). A whole-brain PPI analysis examining whether the VS showed differential connectivity for far and close trials was conducted, but no brain regions identified by this analysis survived family-wise error correction. Moreover, age did not predict differential VS connectivity for far versus close trials in any brain regions.

**Effects of BMI percentile.** Across both close and far trials, leaner individuals recruited medial PFC more strongly than heavier individuals did (see Table S6 in the Supplemental Material). When regulating craving (i.e., on far relative to close trials), leaner individuals activated left vlPFC and parietal cortex more than heavier individuals did (Fig. 4a; see also Table S7 in the Supplemental Material). In a partially overlapping portion of left vlPFC (20 voxels of overlap; MNI coordinates of overlap: −42, 30, 10), an interaction among BMI percentile, condition, and age was observed: Greater BMI predicted less vlPFC activity during regulation in younger, but not older, individuals (Fig. 4b; see Table S8 in the Supplemental Material for additional results). No regions were identified by the interaction between age and BMI percentile.

**Discussion**

This study reveals three key findings about how food craving, and its regulation, varies with age and BMI. First, across experimental conditions, older age predicted less craving, attenuated VS responses, and enhanced lateral prefrontal recruitment. Second, both behavioral and neuroimaging data showed that children and adolescents can use reappraisal to regulate food craving. Third, greater BMI predicted diminished vlPFC recruitment during reappraisal, particularly among children. These data have significant implications for basic and translational work on childhood obesity.
Implications for developmental models of cognition and motivation

The prevalence of overweight and obese youth has increased in the United States over the past 20 years and remains high (Ogden et al., 2012). Despite widespread concern over the implications of this trend, no prior work has examined how food craving changes across development. The present results provide insight into how developing cognitive and motivational systems influence food craving. We found that older age predicts decreased craving, decreased activation of subcortical structures

![Brain regions showing differential activation during regulation](image)

**Fig. 3.** Brain regions showing differential activation during regulation (i.e., close > far and far > close contrasts). dlPFC = dorsolateral prefrontal cortex; dmPFC = dorsomedial prefrontal cortex; vlPFC = ventrolateral prefrontal cortex; vmPFC = ventromedial prefrontal cortex.

![Results for analyses including body mass index (BMI)](image)

**Fig. 4.** Results for analyses including body mass index (BMI). The image in (a) shows brain regions where BMI percentile interacted with condition and with condition and age to predict decreased brain activity during regulation (i.e., far > close contrast). To illustrate the BMI × Condition × Age interaction, the graph in (b) shows values for the far > close contrast in left ventrolateral prefrontal cortex (vlPFC; Montreal Neurological Institute coordinates: −54, 33, −12) as a function of BMI percentile, separately for younger (ages 6–12) and older (ages 13–19) participants. Although age was analyzed continuously, participants were split into two age groups for this graph to highlight the interactive effect of BMI and age in predicting vlPFC recruitment during regulation.
involved in reward and emotional processing, enhanced frontostriatal connectivity, and enhanced lateral prefrontal recruitment both when participants simply view food images and when they actively regulate craving.

These age-related effects suggest that children crave food to a greater extent than adolescents or adults do. In contrast, developmental studies using monetary or social incentives, rather than food, have found that VS responses peak in adolescence (Galvan et al., 2006; Somerville et al., 2011; Van Leijenhorst et al., 2010). Together, these findings suggest that age is associated with a shift in what individuals find rewarding—from primary rewards (food) in childhood to social experiences in adolescence (E. E. Nelson, Leibenluft, McClure, & Pine, 2005). Future work may extend this line of research by (a) examining responses to food within individuals longitudinally and (b) examining how factors other than age (e.g., hunger or sleep history—factors that were not evaluated in the present study) influence food craving within individuals.

With age comes an increased tendency to evaluate appetitive stimuli in more sophisticated ways. Consistent with this, our PPI analysis showed that age-related decreases in VS recruitment were paralleled by enhanced vmPFC-striatal connectivity, with stronger connectivity predicting less craving. Studies have shown that vmPFC is critical for integrating past experiences, present context, and goals to update representations of stimulus value (Roy, Shohamy, & Wager, 2012). Whereas vmPFC activation tracks subjective craving, VS activation tracks actual food consumption (Lawrence, Hinton, Parkinson, & Lawrence, 2012), which suggests that the two brain regions play complementary roles in appetitive processing. Thus, developmental changes in vmPFC-striatal connectivity may reflect a growing ability to represent value and reward in ways that extend beyond simple hedonics.

Age-related reductions in craving may also be a downstream effect of increased lateral prefrontal and parietal recruitment. Activation of these regions, which are broadly implicated in cognitive control and emotional regulation, followed two patterns. First, right dIPFC and posterior parietal cortex, structures that support core working memory processes (Rotschky et al., 2012), sustained attention (Langner & Eickhoff, 2013), and reappraisal (Buhle et al., 2013), were recruited during regulation of craving (i.e., far > close) and also showed general age-related increases (i.e., across both the far and close conditions). Second, right vlPFC recruitment, which supports response inhibition (Wager et al., 2005) and inhibition of appetitive impulses (Casey et al., 2011; Somerville et al., 2011), did not differ as a function of condition (i.e., the far > close contrast was nonsignificant) but showed age-related increases in recruitment across conditions. This suggests that older individuals may spontaneously engage cognitive control in response to food, perhaps because of chronic regulatory goals.

By contrast, an age-independent pattern of prefrontal recruitment was observed when participants reappraised the stimuli to regulate craving. Participants of all ages reported less craving when they focused on a food’s visual, rather than appetitive, features and imagined it being farther away. Reduced craving was paralleled by increased recruitment of prefrontal and parietal regions implicated in the cognitive regulation of emotion (Buhle et al., 2013), and by decreased vmPFC recruitment, which supports valuation of stimuli (Roy et al., 2012). At the same time, older age predicted reduced craving during both reappraisal and unregulated responding. These findings are consistent with a growing body of evidence that children can use cognitive strategies to self-regulate, but also that the capacity and tendency to use cognitive strategies improves with age and experience (McRae et al., 2012; H. N. Mischel & Mischel, 1983; W. Mischel & Baker, 1975; Silvers et al., 2012).

Implications for research on obesity in childhood and adolescence

The present study has several implications for basic obesity research as well as for interventions aimed at preventing childhood obesity. With regard to basic research, it is intriguing to consider why food craving decreases with age given epidemiological work showing that obesity rates rise with age, particularly after age 20 (M. C. Nelson, Story, Larson, Neumark-Sztainer, & Lytle, 2008). This pattern could be explained in one of three ways. First, adults may crave food less and eat less food than children and adolescents, but gain weight because of biological or lifestyle factors (e.g., metabolism, sedentarity). Second, craving and consumption may be tightly coupled in childhood but become less so with age, such that adults eat more but experience less craving than younger individuals—a possibility supported by data showing that young adults eat less healthily than adolescents (M. C. Nelson et al., 2008). Third, craving and food consumption may increase in adulthood after decreasing during adolescence—a possibility that was untestable in the present study because of participants’ age range but could be tested in future work.

Also striking was our finding that heavier individuals recruited left vlPFC less strongly than leaner individuals during regulation. This result dovetails nicely with a recent study showing that greater BMI predicts less lateral PFC recruitment during reappraisal in adults (Giuliani et al., 2014). Given that vlPFC recruitment was stronger during reappraisal than during baseline responding to food, our results suggest that although most individuals recruited vlPFC during reappraisal, such recruitment
depended in part on BMI. In light of vIPFC’s involvement in emotion regulation more generally (Buhle et al., 2013), these findings could be interpreted in one of two ways. The first is that heavier individuals recruit vIPFC to a lesser degree because they are less effective at regulating craving. However, this seems unlikely given that BMI did not predict craving. The second possibility is that although all participants were instructed to reappraise the stimuli using the same strategy, heavy and lean individuals implemented reappraisal differently. In prior work, left vIPFC has been more strongly implicated in reinterpretation variants of reappraisal (i.e., generating a narrative that provides an alternative meaning for a stimulus) than in distancing variants like the one used in the present study (Ochsner, Silvers, & Buhle, 2012). That BMI-related differences in vIPFC recruitment were most pronounced in younger individuals suggests that perhaps leaner children incorporate elements of reinterpretation, even when distancing, to a greater extent than heavier children do.

With respect to interventions, it is noteworthy that after little training, participants as young as 6 years learned to regulate craving. It is particularly striking that the reappraisal strategy was so effective given that participants were not explicitly told that it was intended to reduce craving. At present, the majority of childhood obesity interventions aim to restrict access to unhealthy foods or increase access to exercise (Sobol-Goldberg, Rabinowitz, & Gross, 2013). Although changing children’s environments is clearly important, so too is teaching children to regulate cravings that lead to unhealthy choices in the first place. Teaching children how to regulate cravings when they inevitably do encounter temptations deserves to be tested as a tool for combating obesity.

Author Contributions
J. A. Silvers and K. N. Ochsner developed the study concept. J. A. Silvers, C. Insel, A. Powers, B. J. Casey, W. Mischel, and K. N. Ochsner designed the study. J. A. Silvers, C. Insel, A. Powers, and P. Franz collected the data. J. A. Silvers, C. Insel, P. Franz, and J. Weber performed data analyses under the supervision of K. N. Ochsner. J. A. Silvers drafted the first manuscript with extensive input from K. N. Ochsner. B. J. Casey, W. Mischel, and K. N. Ochsner provided critical revisions. All authors approved the final version of the manuscript for submission.

Acknowledgments
We thank Danielle Dellarco, Chelsea Helion, Alexa Hubbard, Natasha Mehta, Gloria Pedersen, and Theresa Teslovich Woo for their help in recruiting and testing participants.

Declaration of Conflicting Interests
The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding
This work was supported by the National Institutes of Health (R01 NICHD 0691780, F31 NIMH 94056).

Supplemental Material
Additional supporting information can be found at http://pss.sagepub.com/content/by/supplemental-data

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