Etiology and Pathophysiology

Food cue reactivity and craving predict eating and weight gain: a meta-analytic review

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Summary

According to learning-based models of behavior, food cue reactivity and craving are conditioned responses that lead to increased eating and subsequent weight gain. However, evidence supporting this relationship has been mixed. We conducted a quantitative meta-analysis to assess the predictive effects of food cue reactivity and craving on eating and weight-related outcomes. Across 69 reported statistics from 45 published reports representing 3,292 participants, we found an overall medium effect of food cue reactivity and craving on outcomes ($r = 0.33$, $p < 0.001$; approximately 11% of variance), suggesting that cue exposure and the experience of craving significantly influence and contribute to eating behavior and weight gain. Follow-up tests revealed a medium effect size for the effect of both tonic and cue-induced craving on eating behavior ($r = 0.33$). We did not find significant differences in effect sizes based on body mass index, age, or dietary restraint. However, we did find that visual food cues (e.g. pictures and videos) were associated with a similar effect size to real food exposure and a stronger effect size than olfactory cues. Overall, the present findings suggest that food cue reactivity, cue-induced craving and tonic craving systematically and prospectively predict food-related outcomes. These results have theoretical, methodological, public health and clinical implications.

Keywords: Craving, cue reactivity, eating behavior, food, weight gain.

For most people, the mere sight or smell of warm chocolate chip cookies initiates a strong desire to eat, also known as *craving*. Such craving is a form of food cue reactivity: a conditioned response to food that is frequently accompanied by increased salivation, physiological arousal and neural activity in regions such as the ventral striatum (VS) (1–7). It has been proposed that as conditioned responses, craving and other forms of food cue reactivity should lead to increased eating behavior and subsequent weight gain (8,9); however, the evidence for this relationship has been inconsistent. We undertook this systematic review and meta-analysis to (i) summarize the findings in this area, (ii) quantitatively assess whether cue reactivity is prospectively associated with eating

and weight gain, (iii) quantitatively assess whether craving specifically is prospectively associated with eating and weight gain and (iv) estimate the magnitude of these predictive relationships if they are found. We further aimed to investigate whether specific types of cue reactivity (e.g. craving versus neural activity) account for more variance in eating and weight gain and to assess the role of potential moderators such as body mass index (BMI), age, dietary restraint and gender. Assessing contributors to eating and weight gain is especially important given rising rates of obesity in the USA, in what has been described as a 'toxic food environment' filled with an abundance of food cues (e.g. in popular advertising) that may induce craving and cue overeating and weight gain.

Food cue reactivity and craving are conditioned responses

In learning-based models of behavior, food is considered an unconditioned stimulus, and food effects (e.g. salivation and digestive processes) are unconditioned responses. After repeated exposure, food-related cues (e.g. the sight of cookies) that are present at the time of eating acquire the ability to *predict* eating, becoming conditioned stimuli that evoke conditioned responses (including those that prepare the body to digest the food (10)). Consistently, animal work has demonstrated that cues experimentally paired with food (e.g. the sound of a bell) evoke strong conditioned responses, including salivation in dogs (11), ghrelin secretion in sheep (12) and dopamine neuron firing in monkeys and rats (13,14).

For humans in the natural ecology, food cues that become conditioned are typically environmental, such as the sight and smell of food, but can also include interoceptive cues such as stress, negative affect, hormonal fluctuation and food-related cognitions (e.g. (15)). Such conditioned cues consistently induce conditioned physiological responses including increased salivation, heart rate, gastric activity and neural activity in the VS (1–7). According to the 'cued over-eating' model (8,9), these physiologically conditioned responses are consciously experienced as craving and are commonly termed *cue-induced craving* (Table 1). Indeed, exposure to food cues strongly and reliably produces the conscious experience of craving, defined here as 'an intense desire or urge to eat' (8,16–20). Importantly, recent experimental work has shown that conditioned cue craving associations are learned quickly and robustly in the laboratory (21–24) so that even previously neutral stimuli paired with chocolate elicit cue-induced responses, including self-reported craving, after a single-session classical conditioning procedure (25).

Cue reactivity and craving may increase eating and weight

The 'cued overeating' model (8,9) predicts that cue reactivity, and its consciously experienced form of craving, increase the likelihood and amount of food intake. Consistent with this prediction, both cue exposure and responses to cues are associated with subsequent food seeking and

eating in animals (14,26–29). Interestingly, exposure to cues previously associated with high-calorie foods not only increases consumption of those high-calorie foods but also increases consumption of other foods (29). In humans, food cue exposure has been shown to increase eating in adults (16,22,30–41) and children (1,42–49). Similarly, cue-induced physiological responses and neural activity have been prospectively associated with eating (1–4,50–52) and weight gain (53–55), including in children (55). The experience of cue-induced craving specifically has also been linked to subsequent eating behavior (3,16–19). Another form of craving, *tonic craving*, arises independently of external cues (56) and is typically measured using multi-item craving scales that ask about experiences of craving, such as "thinking about my favorite foods makes my mouth water" or "if I am craving something, thoughts of eating it consume me" (57). Like cue-induced craving, tonic craving has been associated with increased eating (58–62) and long-term weight gain (63–66).

However, for both cue reactivity and craving, *some studies have failed to show associations with increased eating and weight* (22,34,35,40,41,52,67–71), while other studies found this association with physiological cue reactivity but not craving (53–55,72). These inconsistencies suggest that either (i) all forms of cue reactivity, including craving, increase eating and weight gain, but that some studies were not able to capture this relationship, (ii) cue reactivity leads to increased eating and weight gain, but this does not depend on the conscious experience of craving or (iii) cue reactivity of any form does not reliably increase eating or weight gain. The present meta-analysis was designed to resolve among these accounts by quantitatively summarizing across all studies, including those that report no association between cue reactivity or craving and eating or weight outcomes. This investigation is important because these processes may influence important health-related outcomes, such as obesity (73).

Potential impact of cue reactivity and craving on obesity

Today, two-thirds of the USA is overweight or obese, whereas only 15% were 30 years ago (74). This is concerning because obesity is currently the second leading cause of preventable disease and death in the USA (75), with elevated BMI accounting for about 2.8 million deaths each year worldwide (76). Population-level shifts in rates of obesity involve broad environmental changes as well as individual-level processes (77–85). On a population level, environmental factors include ubiquitous advertising for appetizing, high-calorie foods (86,87), which some have described as part of a 'toxic food environment' (84,88). Accordingly, individuals who live in a food environment that includes advertised, high-caloric foods (e.g. fast food, such

Table 1   Definitions of the most frequently used terms in this manuscript

Useful definitions
Cue reactivity: conditioned responses to cues, including physiological reactivity and craving
Craving: a strong, conscious desire
Cue-induced craving: self-reported craving in response to cues
Tonic craving: self-reported craving in the absence of external cues

as McDonalds) eat those foods more frequently and have higher BMI (adults: (89–91); children: (92)).

Concurrently, processes such as cue reactivity and craving could explain how such environmental factors influence eating behavior and weight gain on the individual level. Although weight gain involves complex interactions between environmental and physiological systems, these conditioned, learning-based processes may contribute to rising rates of obesity (8,9,84,88,93,94) and low efficacy in weight loss interventions (95–100). For instance, pervasive exposure to food advertisements may strengthen the salience of food cues and their effects on physiological cue reactivity and craving, leading to more frequent food consumption (86). If these processes systematically lead to increased eating and weight, they can serve as important targets for public health and clinical intervention and can facilitate the development of new treatments to prevent and combat rising rates of obesity.

Parallels with drug cue reactivity and drug craving

Over the past 25 years, cue reactivity and craving and their ability to predict clinical outcomes have been most thoroughly investigated in the context of drug addiction. Although some comparisons between drug addictions and eating behaviors remain controversial (101–104), many parallels are evident in work on drug cues and food cues, and the craving responses they elicit. For example, a wealth of animal studies has shown that cues paired with drug taking (i.e. 'drug cues') elicit a variety of conditioned responses and become conditioned predictors of drug taking (105,106). In humans, such drug cues may include the sight of drugs, drug paraphernalia, images of drug taking or of people previously associated with drug cues (107). Several meta-analyses have demonstrated that, in response to such drug cues, drug users show increased physiological reactivity (e.g. heart rate and skin conductance) (108), exhibit increased neural activity in the VS (109–112) and report drug craving (108). In turn, both drug cue exposure and self-reported craving for drugs increase the likelihood of subsequent use across drugs of abuse, including nicotine, alcohol, cocaine, methamphetamine and opioids (for review, see (113)). Much of this work supported the recent inclusion of self-reported craving for drugs as one of the DSM-5 diagnostic criteria for substance use disorders (20). However, although drug and food cue reactivity involve similar learning-based processes, unlike for addictions, food craving is not a standard clinical or diagnostic measure for obesity or eating disorders. Nevertheless, for food as with drugs, cue reactivity, and particularly the conscious experience of craving, may be important predictors of outcomes related to eating behavior, obesity and eating-related psychopathology.

The present investigation

Cue reactivity and craving for food are conditioned responses that have been associated with increased food consumption and weight gain in some studies; however, findings have been inconsistent, and the validity and strength of these effects are an ongoing question. To address this, we conducted a systematic review and quantitative meta-analysis investigating the prospective effect of (i) food cue reactivity, (ii) cue-induced craving and (iii) tonic craving on food-related outcomes, in order to determine how strongly these factors predict eating behavior and weight. We hypothesized that we would find significant prospective relationships between these three factors and food-related outcomes (Hypotheses 1–3). We also hypothesized that BMI, age, dietary restraint and gender would moderate cue reactivity effects (Hypothesis 4) and that exposure to visual food cues would be as powerful as *in vivo* exposure to 'real food' (Hypothesis 5). Overall, we expected medium-sized effects, with cue reactivity and craving explaining a significant amount of variance in subsequent outcomes.

Methods

Literature search and study selection

We conducted literature searches using PubMed and Google Scholar. Searches included the keywords 'food' or 'eat*' or 'weight' or 'BMI', in combination with 'crave' or 'craving' or 'urge' or 'desire' or 'cue reactivity' or 'cue'. We conducted additional searches using the previous search terms and population-specific terms, such as 'dieter' or 'restrained eater' or 'bariatric' or 'overweight' or 'eating disorder'. Further, to ensure that we included as many relevant studies as possible and to identify additional studies that fit inclusion criteria, we searched reference sections of included papers and of relevant literature reviews and performed reverse searches on included papers using Google Scholar. These searches yielded a total of 9,387 independent entries for papers published before October 2014, which were screened by three independent researchers and narrowed to 337 papers (see Fig. 1 for schematic depiction, using the preferred reporting items for systematic reviews and meta-analyses (114)).

We ultimately included studies that met the following criteria: (1a) participants were exposed to a food cue and/or (1b) completed a self-report craving measure;(2) at least one unhealthy food consumption or weight outcome measure was reported; (3) cue exposure and/or craving was measured *before* the eating or weight outcome measure (i.e. prospectively, not retrospectively or cross-sectionally); and (4) at least one reported analysis assessed the relationship between self-reported craving, cue exposure condition or any measure of cue reactivity and outcome. Measures of
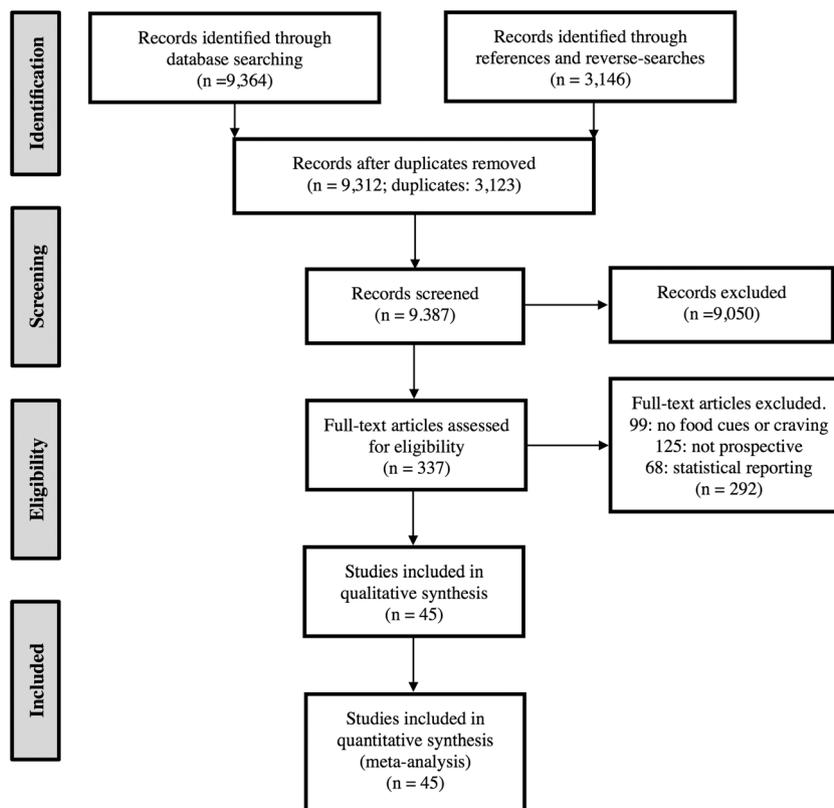
Figure 1 Study selection and exclusion Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) diagram depicting study selection and exclusion.

cue reactivity included (i) cue-induced peripheral physiological reactivity (e.g. heart rate and salivation), (ii) cue-induced fMRI activation and (ii) cue-induced craving. We limited fMRI results to the VS because the VS is necessary for Pavlovian conditioning (115) and has been consistently associated with cue reactivity for both drugs (109,110) and food (5), and with self-reported craving for both drugs and food (116). Final inclusion/exclusion was determined independently by the two authors, yielding 45 studies included in analyses. Any conflicts were discussed between the authors until full agreement was reached.

Data extraction and reduction

From each included study, we extracted N (number of included participants), outcome type (food consumption, weight or BMI), timing of outcome measure (immediately following to two years later), means and standard deviations for cue-conditions and the reported statistics (see Table 2 for additional details). We further coded each study as belonging to one of several study types: (i) 'cue-condition' included studies that reported outcomes after exposing participants to food-related cues (such as visual cues, olfactory cues or real food) compared with a control condition, (ii) 'cue reactivity' included studies that reported

statistical relationships between peripheral physiological reactivity (e.g. heart rate, gastric activity and salivation) or neural activity in response to food cues and outcomes, (iii) 'cue-induced craving' included studies that reported relationships between self-reported craving in response to food cues and outcomes and (4) 'tonic craving' included studies that measured craving in the absence of external cues and reported its relationship with outcomes.

Each piece of information was extracted and coded by one of the two authors and then checked by the other. Any inconsistencies were resolved in discussion until perfect agreement was reached. Extracted statistics fell into several categories:

1. Between-group comparisons between cue-exposure and no-cue exposure groups on food consumption (F or t statistics);
2. Within-group comparisons between cue-exposure and no-cue exposure conditions (F or t statistics);
3. Standardized beta weights (β) from multiple regression models predicting the effect of cue-exposure, cue-reactivity or self-reported craving on eating or weight outcome;
4. Pearson correlation coefficient (r) as an index of effect size of the relationship between cue-response and

Table 2 Characteristics of included studies

Author	Year	Measures	N	Study type	Cue type	Clinical	BMI	Restraint	Gender	Age	Outcome
Batra[†]	2013	Behavioral	95	TC	Real food	No	OW/OB	—	Mixed	Adult	Weight
Birch*	1989	Behavioral	29	CC	Other	No	—	—	Mixed	Children	Eating
Boutelle	2014	Behavioral	15	CC	Other	No	OW	—	Mixed	Children	Eating
Buckland*	2013a	Behavioral	21	CC	Olfactory	No	Lean/OW	Both	Female	Adult	Eating
Buckland*	2013b	Behavioral	13	TC	Real food	No	Lean/OW	Both	Female	Adult	Eating
Buijzen[†]	2008	Behavioral	234	CC	Visual	No	—	—	Mixed	Children	Eating
Coehlo, Ilder	2011	Behavioral	58	CC	Olfactory	No	Lean/OW	Both	Female	Adult	Eating
Coehlo, Jansen*	2009	Behavioral	48	CC	Real food	No	Lean/OW	Both	Female	Adult	Eating
Coehlo, Polivy*	2009	Behavioral	104	CC	Olfactory	No	Lean/OW	Both	Female	Adult	Eating
Cornell*	1989	Behavioral	52	CC/CIC	Real food	No	Lean/OW	Yes	Mixed	Adult	Eating
Cushing	2014	Behavioral	16	TC	—	Bariatric	OW/OB	—	Mixed	Children	Weight
Demos	2012	fMRI	48	CR	Visual	No	Lean/OW	—	Female	Adult	Weight
Fedoroff*	1997	Behavioral	91	CIC	Olfactory	No	—	Both	Female	Adult	Eating
Fedoroff[†]	2003	Behavioral	132	CIC	Olfactory	No	—	Both	Female	Adult	Eating
Ferriday	2008	Behavioral	50	CC	Real food	No	Lean/OW	Both	Female	Adult	Eating
Folkvord	2013	Behavioral	270	CC	Visual	No	Lean/OW	—	Mixed	Children	Eating
Folkvord	2014	Behavioral	261	CC	Visual	No	Lean	—	Mixed	Children	Eating
Gilhooly[†]	2007	Behavioral	32	TC	—	No	OW	Both	Female	Adult	Weight
Halford, Boyland*	2007	Behavioral	93	CC	Real food	No	Lean/OW/OB	—	Mixed	Adult	Eating
Halford, Gillespie*	2004	Behavioral	42	CC/CR	Visual	No	Lean/OW/OB	—	Mixed	Children	Eating
Harris	2012	Behavioral	152	CC	Visual	No	—	—	Mixed	Children	Eating
Jakubowicz[†]	2012	Behavioral	193	TC	Real food	No	OW/OB	—	Mixed	Children	Weight
Jansen, Nederkoorn, Roefs*	2011	Behavioral	58	CC	Real food	No	—	Yes	Mixed	Adult	Eating
Jansen, Nederkoorn, van Baak*	2009	Behavioral	12	CC	Real food	No	Lean/OW	Yes	Female	Adult	Eating
Jansen, Theunissen*	2003	Behavioral	16	CR	Real food	No	Lean/OW	—	Mixed	Children	Eating
Jansen and van den Hout*	1991	Behavioral	19	CC	Real food	No	—	Both	Female	Adult	Eating
Jansen, Vanreyten*	2008	Behavioral	91	CC	Real food	No	Lean/OW	—	Female	Adult	Eating
Lambert*	1991	Behavioral	23	CC	Visual/Real	No	—	No	Mixed	Adult	Eating
Larsen	2012	Behavioral	109	CC	Olfactory	No	Lean	Both	Female	Adult	Eating
Lawrence[†]	2012	fMRI	25	CR	Visual	No	Lean/OW	—	Female	Adult	Eating
Lopez*	2014	fMRI	31	CR/CIC	Visual	No	—	Both	Female	Adult	Eating
Martin[†]	2008	Behavioral	91	TC	Real food	No	OW/OB	—	Mixed	Adult	Eating
Mehta[†]	2012	fMRI	23	CR	Visual	No	Lean/OW/OB	—	Mixed	Adult	Eating
Murdaugh	2012	fMRI	25	CR	Visual	No	OW/OB	—	Mixed	Adult	Weight
Nederkoorn	2002	Behavioral	44	CR	Real food	Both	Lean	Both	Female	Adult	Eating
Nederkoorn, Jansen	2000	Behavioral	24	CR/CIC	Real food	No	Lean/OW	No	Female	Adult	Eating
Nederkoorn, Smulders*	2004	Behavioral	72	CR/CIC	Real food	Both	Lean	—	Female	Adult	Eating
Ng*	2013	Behavioral	50	CIC	Real food	Both	OW/OB	—	Female	Adult	Eating
Overduin	1997	Behavioral	20	CC	Other	No	Lean	—	Mixed	Adult	Eating
Rogers*	1989	Behavioral	12	CR	Visual	No	Lean	Both	Female	Adult	Eating
van den Akker	2013	Behavioral	70	CC	Other	No	Lean	No	Female	Adult	Eating
Vogele and Florin*	1996	Behavioral	60	CR/CIC	Real food	Both	Lean/OW	Both	Mixed	Adult	Eating
Wonderlich-Tierney	2013	Behavioral	83	CC	Visual	No	Lean/OW	—	Mixed	Adult	Eating
Yokum	2014	fMRI	24	CR	Visual	No	Lean/OW/OB	—	Mixed	Children	Weight
Zoon	2014	Behavioral	50	CC	Olfactory	No	Lean/OW	Both	Female	Adult	Eating

*studies that contributed multiple independent, nested effect sizes;

[†]studies that contributed multiple effect sizes and were averaged to adjust for non-independence. CC, cue condition studies (reported outcomes after exposing participants to food-related cues compared with a control condition); CR, cue reactivity studies (reported statistical relationships between physiological reactivity (e.g. heart rate, gastric activity and salivation) or neural activity in response to food cues and outcomes); CIC, cue-induced craving studies (reported relationships between self-reported craving in response to food cues and outcomes); TC , tonic craving studies (measured craving in the absence of cues and reported its relationship with outcomes); OW, overweight; OB, obese.

subsequent eating or weight outcome. Cue-responses were either (a) cue-induced physiological reactivity (e.g. heart rate, salivation), (b) cue-induced neural response in VS, or (c) cue-induced craving;

5. Pearson correlation coefficient (r) as an index of effect size of the relationship between tonic measures of craving and subsequent eating or weight outcome.

We also extracted information about potential moderators, including participant pre-study BMI (lean/overweight, measured prior to cue exposure/craving measurements), participant age (children/adults), restrained eating status (restrained eaters/non-restrained eaters), gender (male/female/mixed) and type of food cue (real food/visual/olfactory/other). We included any reported measure of BMI and

restrained eating status. Further, we defined a sample as representing 'children' when the mean age was <18 years. This set of studies ($N_{STUDIES} = 11$) included children and adolescents ages 3–17 years. Examining these moderators in this meta-analysis could identify differences in the strength of cue reactivity effects and explain variability in findings and/or effect sizes across different studies (see Supporting Information for additional details).

Statistical analyses

All analyses were conducted using the Comprehensive Meta-Analysis Version 3.0 software program (Biostat; Englewood, NJ, 2015) (117), following previously published meta-analyses (118–121).

Calculation of effect sizes

For between-group and within-group comparisons, means, standard deviations and/or test statistics were used to calculate Cohen's d, and then d was converted to Pearson's r (122,123). For beta weights, we used imputation to convert β to r (124). The inclusion of beta weights in meta-analyses is somewhat controversial, because beta coefficients reflect the influence of all predictor variables in a regression equation. Nevertheless, we decided to include them for several reasons: (i) such studies directly test for a predictive relationship between cue reactivity measures and food outcome and are therefore relevant to this meta-analysis, (ii) such beta coefficients are actually more conservative than r (123), (iii) omitting them would increase the sampling error (123,124), (iv) empirical work has found that r can be reliably imputed from β values (124) and (v) such methods have been successfully used in published meta-analyses (e.g. (125,126)). Pearson's correlation coefficients (r) (those extracted from included studies as well as those converted from other statistics) were converted to a standard normal z-score metric using Fisher's r–z transformation (127). After all effect sizes were converted to z-scores, each effect size was weighted based on sample size and used to create an average effect size r, as in previously published meta-analyses (e.g. (119,120,128,129)). We used Cohen's criteria for small ($r = 0.10$), medium ($r = 0.30$) and large ($r = 0.50$) effect sizes (130).

Adjusting for dependencies in effect size

Several studies reported multiple non-independent statistics using the same study population (e.g. multiple correlation coefficients between craving and consumption of several food types; see Table 2 for details). In these cases, we aggregated non-independent effect sizes by averaging reported statistics. In cases in which studies reported several independent statistics (e.g. in independent participant groups within a study), we reported these as 'nested' statistics within these studies. For instance, we included two correlation coefficients from a single study when they independently represented

overweight and lean individuals (1,47,48,131) and independently restrained and unrestrained eaters (17,18,31,33,60). We also included multiple statistics when they independently represented different cue conditions (e.g. olfactory versus control and visual versus control (4,17)) or independent measures of craving (e.g. self-report by scale and cue-induced craving (3,48,50,132,133)). This approach is analogous to methods used in previously published meta-analyses (118,120).

Meta-analytic random effects models

We applied random effects models to the main analyses because we expected differences in sample and methodology across studies and wanted to allow for population inferences (122,127). Such models are more conservative and have lower Type I error rates than fixed effects models, and allow for generalizability of findings across new samples. We also calculated a Q statistic to measure heterogeneity in effect sizes across studies. For moderator-based analyses, a significant Q would suggest that compared groups (e.g. high versus low BMI) exhibit different relationships between cue reactivity or craving and outcome. Because we included a relatively small number of studies in our moderator analyses (see previous discussion), we evaluated moderators even in the absence of a significant Q, as suggested by Rosenthal and DiMatteo (123). Further, we used mixed models to test the effects of categorical moderators (e.g. gender, dietary restraint and fixed) on study effect sizes (random).

Publication bias

Because studies with non-significant findings may not be published, and therefore cannot be included in meta-analyses (i.e. 'the file drawer problem'), we conducted the most conservative analyses of publication bias to assess the effect of missing studies on meta-analytic results using two approaches (134). First, we calculated Rosenthal's fail-safe N to determine the number of studies with a null effect that would be necessary to render the meta-analytic results non-significant ($p > 0.05$) (123). Using a second approach, we created a funnel plot depicting standard error by Fisher's z (135), assessed for publication bias (136–138) and conducted a trim-and-fill analysis (139,140) to estimate the number of studies with negative findings that are potentially missing from the literature.

Results

Included studies and outcome variables

Of the 12,510 articles initially identified through online, reverse and reference searches, 3,123 were duplicates, and 9,387 were screened for eligibility. Nine thousand fifty were initially excluded (primarily for studying animals, not including an outcome variable or not measuring food cue reactivity/craving), and 337 studies were fully assessed for

eligibility. Of these, 99 studies were excluded for not containing food-related cues or not measuring cue reactivity, 125 for not prospectively testing the effect of cue reactivity on outcomes and 68 for not reporting statistics of interest. Ultimately, 45 studies were included in analyses, with 69 reported statistics, representing 3,292 participants (Fig. 1). Of the statistics included, 35 were 'cue-condition' statistics ($N_{PARTICIPANTS} = 1,834$), 15 were 'cue-reactivity' statistics ($N_{PARTICIPANTS} = 458$), 12 were 'cue-induced craving' statistics ($N_{PARTICIPANTS} = 546$) and 7 were 'tonic craving' statistics ($N_{PARTICIPANTS} = 454$). We included 53 statistics from behavioral studies ($N_{PARTICIPANTS} = 2,520$), 8 from fMRI ($N_{PARTICIPANTS} = 248$) and 8 from other psychophysiological measures (e.g. salivation/heart rate; $N_{PARTICIPANTS} = 524$; Table 2).

In addition, 35 statistics included overweight or obese individuals ($N_{PARTICIPANTS} = 1,649$) and 18 included restrained eaters ($N_{PARTICIPANTS} = 919$). Forty-two statistics were female-only samples ($N_{PARTICIPANTS} = 1,749$), 26 statistics were from mixed male/female samples ($N_{PARTICIPANTS} = 1,523$) and only one statistic represented males only ($N_{PARTICIPANTS} = 20$). Nineteen statistics included a mean age under the age of 18 years ('children'; $N_{PARTICIPANTS} = 953$).

Thirty-two statistics measured responses to real food cues, whereas 13 measured responses to olfactory cues, 17 to visual cues (pictures and videos) and 2 used 'other' cue types (e.g. auditory and environmental). $N_{STUDIES} = 39$ included exposure to cues, of which $N_{STUDIES} = 34$ reported the length of exposure to food cues (Range$_{MINUTES}$: 0.5–40, Mean$_{MINUTES}$ = 9.73 and SD$_{MINUTES}$ = 7.97) and $N_{STUDIES} = 5$ did not report length of exposure to cues.

The outcome variable from 54 statistics was food amount consumed immediately following a laboratory manipulation (measured in grammes or calories; $N_{PARTICIPANTS} = 2,457$). Eight statistics reported food amount consumed over 1–2 weeks after the study period ($N_{PARTICIPANTS} = 391$) and 7 statistics reported change in weight or BMI over time (4 months–2 years; $N_{PARTICIPANTS} = 444$; Table 2). Sample size of individual studies ranged from $N_{PARTICIPANTS} = 3$ to 234, with a mean sample size of 66.51 (SD = 53.06).

Overall effect on outcomes

We first performed an omnibus analysis across all the included studies ($N_{STUDIES} = 45$, $N_{PARTICIPANTS} = 2,948$) and found a significant overall combined effect size of $r = 0.33$ (CI: 0.27–0.38, $z = 10.69$, $p < 0.001$), suggesting a medium prospective effect of cue reactivity and craving on eating and weight-related outcomes. Overall, cue reactivity and craving measures explained approximately 11% of variance in subsequent eating and weight-related outcomes.

Next, we compared effect sizes for food and weight-related outcomes separately. The type of outcome measure

did not influence effect size ($Q_{(1)} = 0.68$, $p = 0.41$). Tested separately, cues and craving had medium effects on both eating ($r = 0.32$, CI: 0.26–0.38, $z = 9.53$, $p < 0.001$) and weight outcomes ($r = 0.39$, CI: 0.23–0.53, $z = 4.59$, $p < 0.001$). Finally, long-term outcome measures were associated with larger effect sizes than short-term outcomes ($Q_{(1)} = 4.30$, $p = 0.04$; same day; $r = 0.30$, CI: 0.24–0.36, $z = 8.93$, $p < 0.001$; >1 week; $r = 0.43$, CI: 0.32–0.52, $z = 7.19$, $p < 0.001$; Figs. 2 and 3).

Hypothesis 1: Effect of Food Cue Reactivity on Outcomes.

To test the hypothesis that food cue reactivity predicts outcomes, we calculated the average effect size across all cue condition and cue reactivity studies (including cue-induced craving, neural activity and peripheral physiology, but excluding tonic craving). We found a significant overall combined effect size of $r = 0.33$ (CI: 0.27–0.40, $z = 9.73$, $p < 0.001$; Fig. 3), suggesting a medium effect of cue reactivity on eating and weight outcomes, accounting for 11% of the variance. Type of outcome measure did not influence effect size ($Q_{(1)} = 2.04$, $p = 0.15$). Cue-condition and cue reactivity paradigms had medium-to-large effects on both eating ($r = 0.32$, CI: 0.26–0.39, $z = 9.08$, $p < 0.001$) and weight outcomes ($r = 0.51$, CI: 0.26–0.69, $z = 3.69$, $p < 0.001$). In addition, we found that cue reactivity had a larger effect on longer-term outcomes ($Q_{(1)} = 7.20$, $p < 0.01$; same day: $r = 0.29$, CI: 0.23–0.36, $z = 8.56$, $p < 0.001$; >1 week: $r = 0.48$, CI: 0.36–0.59, $z = 6.98$, $p < 0.001$).

To examine whether type of food cue reactivity exhibited different relationships with outcome, we compared across types of cue condition and cue reactivity studies. We did not find a significant difference, with all study types averaging a medium effect size ($Q_{(1)} = 3.73$, $p = 0.16$; cue-induced craving: $r = 0.40$, CI: 0.27–0.52, $z = 5.74$, $p < 0.001$; cue-condition: $r = 0.29$, CI: 0.22–0.36, $z = 7.58$, $p < 0.001$; cue reactivity: $r = 0.41$, CI: 0.28–0.52, $z = 5.83$, $p < 0.001$). Within cue reactivity studies, we did not find a significant difference between peripheral physiological and neutral activity measures ($Q_{(1)} = 0.74$, $p = 0.39$; physiology: $r = 0.35$, CI: 0.23–0.46, $z = 5.27$, $p < 0.001$; neural: $r = 0.42$, CI: 0.30–0.53, $z = 6.15$, $p < 0.001$), such that both were significantly related to outcomes.

Hypotheses 2 and 3: Effect of Cue-induced Craving and Tonic Craving on Outcomes

Next, to test the hypothesis that craving predicts outcomes, we averaged effect sizes for studies that included cue-induced craving or tonic craving measures. We found that craving had a medium effect size on outcomes ($r = 0.33$, CI: 0.27–0.40, $z = 9.40$, $p < 0.001$), which did not vary based on short versus
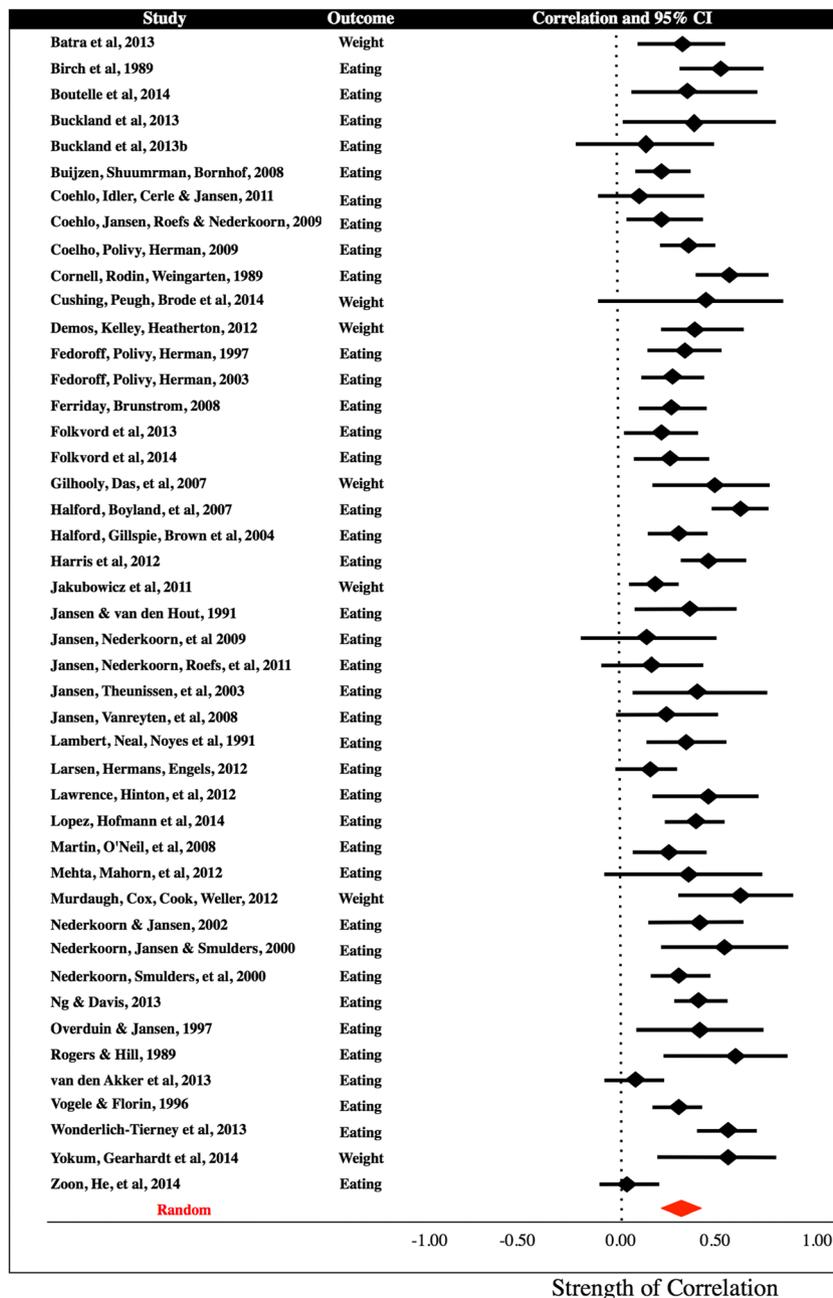
Figure 2 Forrest plot of effect sizes. Statistics were converted to a standardized *r* and are plotted with 95% confidence intervals. The x-axis indicates the strength of the correlation coefficient, and shows that the overall effect favours a positive relationship between variables.

long-term outcomes ($Q_{(1)} = 1.55$, $p = 0.21$; Fig. 3). Then, we compared the effect sizes of cue-induced and tonic craving measures. We found no difference in effect sizes ($Q_{(1)} = 3.41$, $p = 0.10$), such that cue-induced craving and tonic craving each contributed significantly to outcomes (cue-induced: $r = 0.38$, CI: 0.30–0.46, $z = 8.36$, $p < 0.001$; tonic: $r = 0.27$, CI: 0.18–0.36, $z = 5.77$, $p < 0.001$). All cue-induced craving studies reported eating outcomes. Tonic craving predicted both eating ($r = 0.26$, CI: 0.08–0.42, $z = 2.75$, $p < 0.001$)

and weight outcomes ($r = 0.27$, CI: 0.17–0.37, $z = 5.07$, $p = 0.001$) to the same degree ($Q_{(1)} = 0.02$, $p = 0.89$).

Hypotheses 4 and 5: Effects of Moderator Variables

Body mass index

To test whether pre-study BMI moderated the effects of cue reactivity and craving on outcome, and was therefore
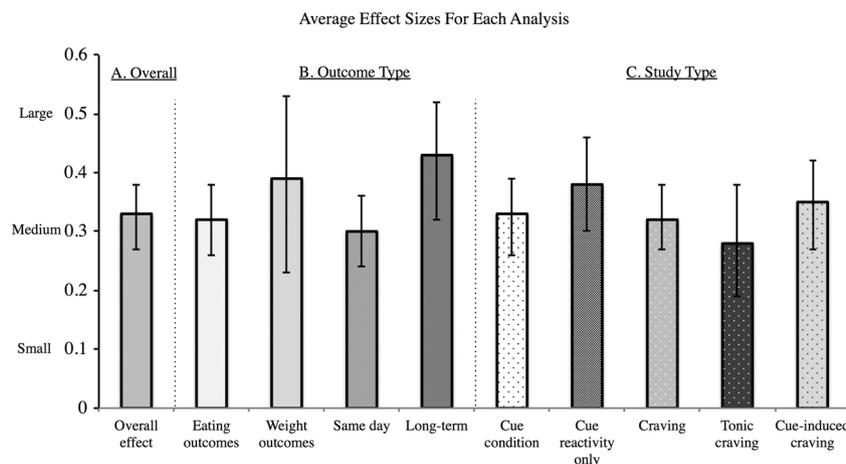
Figure 3 Average effect sizes for Hypotheses 1–3. Average effect sizes and confidence interval: (A) overall, across all study types; (B) separately by outcome type; and (C) separately by study type. All effect sizes are medium or medium-to-large following Cohen's *d* convention. 'Cue condition' includes all studies that measured responses to cue exposure, including cue-condition, cue reactivity (physiological and neural) and cue-induced craving. 'Craving' includes both tonic and cue-induced craving. The effect size in males represents $N_{\mathrm{STATISTICS}} = 1$.

associated with variability in effect sizes, we compared statistics with lean participants (BMI ≤ 24.9) to those with overweight or obese participants (BMI ≥ 25). Studies that did not explicitly report participant BMI or included mixed samples were excluded from this analysis ($N_{\mathrm{STUDIES}} = 26$). We found no effect of BMI group ($Q_{(1)} = 0.89$, $p = 0.35$). Samples with lean participants ($r = 0.30$, CI: 0.17 - 0.43, $z = 4.28$, $p < 0.001$) and overweight participants ($r = 0.40$, CI: 0.25 - 0.53, $z = 4.85$, $p < 0.001$) both exhibited significant, medium-sized relationships between cue-reactivity/craving and outcomes (Figure S1).

Age
We tested whether studies with samples of children (mean age < 18) or adults showed stronger effects. We did not find a significant difference in effect sizes between adults and children ($Q_{(1)} = 2.88$, $p = 0.09$). Studies with adults and children both exhibited medium effect sizes of cues/craving on eating and weight outcomes (children: $r = 0.40$, CI: 0.30–0.50, $z = 7.14$, $p < 0.001$; adults: $r = 0.30$, CI: 0.24–0.36, $z = 8.84$, $p < 0.001$; Figure S1).

Restrained eating
To test whether restrained eating is associated with a larger effect of cue reactivity and craving on eating and weight, we compared statistics with restrained eaters to those with non-restrained eaters. We included all reported measures of dietary restraint. Studies that did not explicitly assess dietary restraint or that only reported statistics from mixed samples were excluded from this analysis ($N_{\mathrm{STUDIES}} = 29$). We did not find a significant difference based on dietary restraint ($Q_{(1)} = 2.90$, $p = 0.09$). The effect sizes for restrained eaters was medium-sized ($r = 0.31$, CI: 0.20 - 0.42, $z = 5.12$, $p < 0.001$)

and for non-restrained eaters was small-to-medium ($r = 0.19$, CI: 0.10–0.28, $z = 4.05$, $p < 0.001$; Figure S1).

Gender
A single study reported separate statistics for male participants. Therefore, to examine whether gender influences the magnitude of association, we compared 42 statistics with women only ($N_{\mathrm{PARTICIPANTS}} = 1,749$), 26 mixed gender ($N_{\mathrm{PARTICIPANTS}} = 1,523$) and one with male-only participants ($N_{\mathrm{PARTICIPANTS}} = 20$). We found a significant effect of gender ($Q_{(2)} = 9.61$, $p = 0.01$), such that the effect size for mixed-gender samples was larger than for females. Despite this, the effect size for females and mixed-gender samples were both medium (female: $r = 0.28$, CI: 0.21–0.34, $z = 8.01$, $p < 0.001$; mixed: $r = 0.39$, CI: 0.32–0.46, $z = 9.73$, $p < 0.001$). The one effect size in males was large, with a sizable confidence interval, although this single effect size should be interpreted with caution ($r = 0.73$, CI: 0.35–0.90, $z = 3.26$, $p = 0.001$; Figure S1). Differences between mixed and female samples remained significant when excluding the single statistic in a male sample. No included studies reported gender-related differences in outcomes.

Food cue type
We tested whether food cue type influenced the magnitude of observed effects and found a significant difference ($Q_{(2)} = 6.28$, $p = 0.04$). Both real food cues and visual cues (pictures and videos) were associated with medium-sized effects on eating and weight (real food: $r = 0.36$, CI: 0.28–0.43, $z = 9.04$, $p < 0.001$; visual: $r = 0.37$, CI: 0.27–0.45, $z = 7.43$, $p < 0.001$). In contrast, olfactory cues were associated with a small-to-medium effect size ($r = 0.21$, CI: 0.09–0.32, $z = 3.42$, $p = 0.001$; Fig. 4).
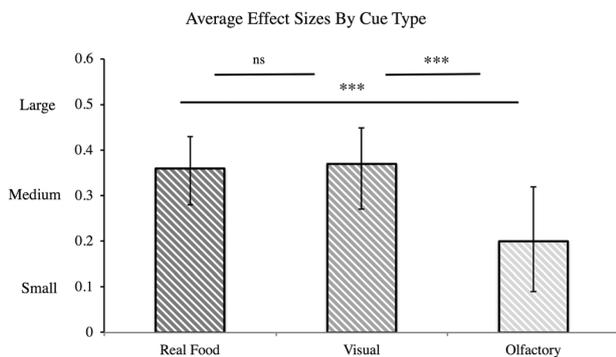
Figure 4 Average effect sizes by cue type (Hypothesis 5). Effect sizes for visual and real food cues were not significantly different; both were significantly bigger than for olfactory cues. '***' indicates that $p < 0.001$.

Figure 5 Funnel plot depicting standard error of effect sizes. Funnel plot shows minimal publication bias in the overall model using the calculated Fisher's z-value for each study in a trim-and-fill analysis. Black circles represent studies included in the analysis, and grey circles represent filled-in studies. The black diamond is the observed effect, and the grey diamond is the adjusted effect after adding the filled-in studies, which is still significant.

Publication bias

First, we calculated Rosenthal's fail-safe N to determine the number of studies with a null effect that would be necessary to render the meta-analytic results non-significant. Overall, the fail-safe N for the omnibus analysis was $N_{STUDIES} = 4,186$. In other words, 4,186 studies with null results would be required to suggest that cue reactivity and craving are not prospectively associated with eating and weight outcomes. Testing separately by type of outcome, we found fail-safe $N_{STUDIES} = 3,015$ for studies reporting eating outcomes and fail-safe $N_{STUDIES} = 89$ for weight outcomes. The fail-safe N across cue condition, cue reactivity and cue-induced craving studies was $N_{STUDIES} = 3,295$ (Hypothesis 1) and fail-safe N for cue-induced craving and tonic craving studies was $N_{STUDIES} = 367$ (Hypotheses 2 and 3; cue-induced $N_{STUDIES} = 141$; tonic $N_{STUDIES} = 48$). For moderator comparisons, the fail-safe Ns were still quite high, with smaller fail-safe Ns corresponding with smaller number of included studies: lean fail-safe $N_{STUDIES} = 306$, overweight $N_{STUDIES} = 234$, children $N_{STUDIES} = 491$, adult $N_{STUDIES} = 1,785$, restrained $N_{STUDIES} = 46$ and non-restrained $N_{STUDIES} = 49$ (Hypothesis 4). Similarly, for cue-type analyses, the fail-safe Ns for real food cues, visual cues and olfactory cues were 5 to 50 times the observed study sample (fail-safe $N_{STUDIES} = 962$, $N_{STUDIES} = 498$ and $N_{STUDIES} = 39$, respectively; Hypothesis 5). Overall, fail-safe N analyses indicated that a very large number of studies reporting null results would be needed to render the reported meta-analytic results non-significant.

Using a second approach, we calculated Kendall's tau and Egger's regression intercept and conducted a trim-and-fill analysis. Kendall's tau ($\tau = 0.36$, $z\tau = 3.27$, $p < 0.01$) indicated some risk of publication bias; however, Egger's regression intercept did not detect bias ($t_{(33)} = 0.84$, $p = 0.27$). The trim-and-fill analysis filled in 15 studies left of the mean and zero studies right of the mean, adjusting to an unbiased effect size $r = 0.24$ (CI: 0.21–0.27; Fig. 5), which is still substantial. Overall, these analyses also suggest that the present meta-analytic results a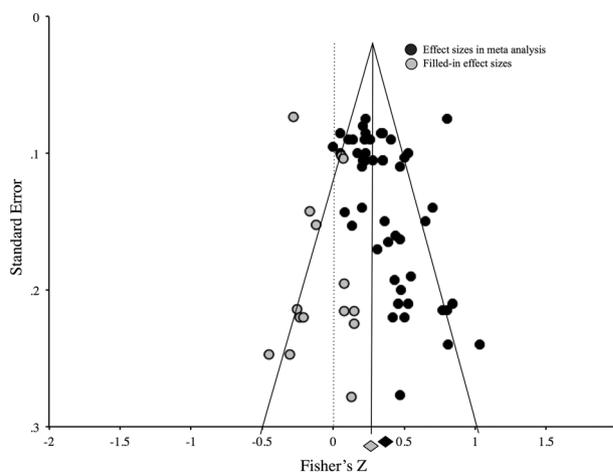re resilient to publication bias and that even adjusting for publication bias, food cue reactivity and craving still predict eating and weight outcome with a medium effect size.

Discussion

The present meta-analysis is the first quantitative examination of the effect of food cue reactivity and craving on subsequent eating behavior and weight gain. Across 45 published studies and 69 reported statistics representing 3,292 participants, we found a significant medium effect ($r = 0.33$) of food cue reactivity and craving on eating and weight, measured prospectively with outcomes in the short-term and long-term. Our results demonstrate a robust prospective and predictive relationship between measures of food cue reactivity, including the conscious experience of craving and subsequent food-related outcomes. Further, we found consistent, medium effect sizes across several specific analyses, in confirmation of our hypotheses. In support of our first hypothesis that cue reactivity increases eating, we found that (i) exposure to food cues increases eating ('cue condition' studies) and (ii) the magnitude of physiological and neural cue reactivity to food cues relates prospectively to eating and weight gain over time ('cue reactivity' studies). In support of our second hypothesis, we found that magnitude of cue-induced craving relates prospectively to eating and weight gain. In support of our third hypothesis, we found that magnitude of tonic craving relates to eating and weight gain prospectively. We also found that real food and visual cues were both more strongly related to outcomes than olfactory cues and that BMI, age, dietary restraint and gender did not modify the strength of the findings. Overall, our results suggest that food cue reactivity and craving explain a substantial

amount (7–26%) of the variance in food-related outcomes. In turn, this suggests a causal effect of cue exposure and craving on eating behavior and weight. Our results have important theoretical and methodological implications for the use and application of food cue reactivity paradigms, as well as implications for our understanding of obesity prevention and treatment.

Theoretical implications

Our work provides strong empirical support for the idea that exposure and reactivity to food cues, including craving, increase eating and weight, and thus may contribute to rising and persistent rates of obesity. Indeed, our findings are consistent with both conditioned, learning-based models (21–24) and their theoretical applications to obesity (80–84,93,94,99,141). For instance, Jansen (8,9) proposed that eating triggered by increased availability and advertising of food can lead to steady weight gain on a population level and interfere with the efficacy of obesity treatment. Although the increasing presence of food and food cues has been described as a 'toxic food environment' that causes a population-wide increase in BMI (e.g. (84,88)), it has been difficult to determine causal relationships between the environment and obesity from cross-sectional studies (142). Importantly, our meta-analytic work demonstrates that responses to food cues systematically lead to subsequent eating and weight gain across both experimental and prospective studies, providing evidence of a consistent, predictive relationship on an individual level. Furthermore, these effects generalize across individual differences in BMI, age, dietary restraint and gender. Thus, our work supports the theory that, on a large scale, the abundance of food and food cues in the modern 'toxic food environment' may function as conditioned stimuli that serve as triggers for increased food consumption and can lead to weight gain on a population level (80–85,93,94,99,141).

Implications for obesity prevention and policy

By establishing the link between food cues and eating, our work can help build a framework to investigate how individual behavior is influenced by environment–level interventions. Because we find that exposure to food cues reliably leads to eating and weight gain, our work is consistent with the suggestion that exposure to food advertisements and increased access to unhealthy foods can have deleterious effects. In that, the findings support obesity prevention policies that reduce unhealthy food cue exposure, including limiting food advertisements or access to high-caloric, nutrient-poor foods. In one analysis, we specifically found that visual exposure to pictures or videos of food (such as in food advertising and commercials) increases eating behavior and weight, including several studies in the present meta-analysis that used real-life

food advertisements as food cues in experimental settings (47,48,143). Accordingly, this could support policy initiatives limiting television and print advertisements for energy dense products (144) as has been previously implemented for cigarettes (145,146). Our findings support the removal of cues to and availability of unhealthy foods in schools, an intervention that has already demonstrated some effectiveness in preventing unhealthy weight gain in children (147). Because we found that cue-related effects are similar in children and adults, these interventions may also be applicable for adults. Indeed, it has been shown that reducing the visibility of food cues in an office environment reduces consumption of unhealthy foods in adults (148). In sum, our work highlights a mechanism involved in food consumption that explains why a reduction in exposure to food cues can be an important target for obesity prevention policies.

Methodological implications

Our work has methodological implications for the use and application of cue reactivity and craving paradigms. Learning-based models suggest that olfactory cues should be better predictors of food consumption than visual cues because olfactory cues are always present during food consumption and the conditioned stimulus that predicts the unconditioned stimulus best should elicit the strongest conditioned responses (8). Consistently, the use of visual stimuli has been criticized for failing to represent real-world food consumption, although it mirrors advertising for food (e.g. (149)). Nevertheless, we found that reactivity to visual food cues (e.g. pictures and videos) is as strongly predictive of eating behavior and weight gain as reactivity to real food (and that both are more strongly predictive than olfactory cues). That visual food cue exposure was as strongly associated with eating behavior as real food exposure suggests that cue-based learning processes are powerful for food. This finding is especially informative for neuroimaging studies that frequently use images to provoke craving (5,53,55,150) and for studies that use images to investigate the regulation of craving (151,152). Overall, our findings support the ecological validity of a variety of food cues (including visual food cues) to elicit cue reactivity and craving and suggest that this directly relates to real-life behavior, because their effect on subsequent food-related outcomes is comparable with real food exposure.

Parallels with drug cue reactivity and addictions

As reviewed earlier, cue reactivity and craving for food and drugs share many similarities. In fact, it has been proposed that drugs 'hijack' a hedonic, dopamine-modulated reward system that originally evolved for food and that subserves processes including cue reactivity and craving for both food and drugs (5,101,153). It is this system that is altered in

addiction and may be altered in obesity and eating disorders (154–156). Here, we report that food cue reactivity and craving predict eating and weight, which further parallels findings in addiction linking drug cue reactivity and craving to drug taking and clinical outcomes for addictive disorders (113,121,157). However, despite such similarities, cue reactivity and craving are central aspects of the diagnosis and treatment of addictive disorders, whereas they are under-utilized in the context of eating behavior.

Some previous proposals to investigate similarities between food and addiction have focused on the concept of 'food addiction' and have been met with controversy (101–104). We propose that continued construct-focused and mechanism-focused investigation into similarities between drug taking and eating behavior may be useful for illuminating shared processes across addictions and eating-related psychopathology (as proposed by the Research Domain Criteria framework (158)). Our work specifically suggests that cue reactivity and craving may be cross-diagnostic and clinically relevant. As such, they could be used to more accurately describe and measure eating behavior, as they have been in addictive disorders. This insight may further encourage the adoption of other paradigms from the addictions field to measure-related processes, such as regulation of craving, impulsivity and cognitive control. Such processes could explain additional variance in food-related outcomes and facilitate comparisons between food and drug-seeking behavior and related psychopathology.

In addition, our work is relevant to an ongoing debate in the addictions literature about the influence of cue-induced versus tonic craving on outcomes (159–163). We found that both tonic and cue-induced craving were associated with subsequent eating and weight-related outcomes, suggesting that both of these forms of craving can serve a predictive function and may be useful to measure in clinical and treatment settings. Finally, these parallels suggest that treatment approaches for obesity and related disorders can draw from insights and findings already established for addiction, as elaborated in the succeeding discussion.

Treatment implications for obesity and related disorders

Our findings are consistent with and suggest explanatory mechanisms for the efficacy of pharmacological, behavioral and psychological treatments for obesity, eating disorders and addictions that both reduce craving and improve outcomes (73,164–166). For example, craving-targeting medications increase weight loss in overweight individuals, paralleling findings in addiction that demonstrate reductions in drug use with pharmacotherapy (167,168). Specifically, pharmacotherapies that reduce craving, such as bupropion and naltrexone, are associated with reduced self-reported craving and reduced BMI in weight loss trials (95,169–172).

In addition, stimulants such as methylphenidate also reduce craving for and consumption of food (173). Similarly, in drug addiction, such pharmacotherapies reduce craving for and consumption of alcohol (174,175), methamphetamine (176) and nicotine (177).

Several psychological treatments also target the associations between cue exposure, craving and food consumption, including cue exposure and response prevention treatments (CERP), cognitive behavioral therapy (CBT) and mindfulness-based therapies (MBTs). CERP attempts to extinguish associations between a cue, conditioned responses and a behavior by preventing the behavior from occurring in a cued context, consistent with learning models (8,9). Such exposures occur over prolonged periods (e.g. 60 min, multiple times per week), in contrast to the relatively short exposures used by studies included in this meta-analysis (e.g. ~10 min) (178–180). Accordingly, prolonged exposure to chocolate cues (181), as well as smoking (182) and alcohol cues (183), reduces physiological reactivity in response to these cues. As a treatment, CERP also reduces self-reported craving (178) and binge eating in individuals with bulimia nervosa (178,180,184,185). However, extinction of cue-response pairings can be context-specific and may therefore still be reinstated in new environments (100,186–189) or through incubation of craving (190), even after extinction, limiting the potential application of CERP. Consistently, clinical trials for CERP have been mixed for other eating disorders (191), obesity (192) and addictions (193,194).

In contrast, other psychological treatment approaches assume that the association between food cues, craving and food consumption may not be perfectly extinguished and provide skills to manage diverse food-related contexts. For instance, CBT employs cognitive and behavioral strategies to reduce the influence of food cues and craving on eating behavior and weight. Cognitive strategies include the regulation of craving through cognitive reappraisal, which reduces neural reactivity and self-reported craving for high-calorie foods (116,151,152,195), cigarettes (116,151), alcohol (196), cocaine (197) and methamphetamine (198). Behavioral strategies to reduce the influence of food cues and craving in CBT include the following: determining the antecedents of eating behavior (e.g. food cues and craving), intervening to prevent consequences (i.e. food consumption), stimulus control (e.g. reduction of food cues in the personal environment), regular meal planning (to reduce vulnerability to food cues and craving) and exposure-based exercises (to reduce the salience of 'trigger' foods and contexts) (199). CBT is effective in the treatment of a wide range of conditions (200), including eating disorders (164,201), obesity (202,203) and drug addictions (204). Further, regulation of food craving specifically has been examined as part of obesity interventions for children (205) and adults (206), although this work is in its early stages. Finally, MBTs that teach individuals to notice and accept the experience of craving have

demonstrated effectiveness at reducing craving for food and weight in both lean and obese adults (207–210) as well as reducing episodes of binge eating in individuals with binge eating disorder (211), bulimia nervosa (212,213) or following bariatric surgery (214). In drug addiction, MBTs reduce craving and use of drugs (215–217), and reductions in craving reportedly mediate reductions in drug use (215,217).

Overall, much evidence suggests that treatments that target cue-outcome associations and/or craving-outcome associations can reduce eating, improve weight outcomes and reduce drug use in addictions. We propose that the findings reported in this meta-analysis provide explanatory mechanisms for the efficacy of such treatments, although this should be investigated directly using mediation models in future clinical work (e.g. (215)). Such continued investigation into craving-targeted pharmacotherapy, behavioral treatment and psychotherapy for obesity and related disorders may increase the efficacy of existing treatment approaches.

Methodological issues and future work

One limitation of this meta-analysis is that it could not include all studies in the field; rather, it was inherently limited to studies that reported appropriate statistics. Unfortunately, approximately 20% of the studies that met our initial inclusion criteria were excluded because of limited or incomplete statistical reporting. This highlights the importance of reporting of sample size, means, standard deviations, test statistics and effect sizes in all future work, in order to increase accurate and transparent data reporting and to contribute to future meta-analyses and the overall development of the field.

Relatedly, we may not have been able to detect significant effects in some of our moderator analyses because of underreporting of group-based statistics or because of a small or imbalanced number of studies included in such analyses. Future work should continue to assess whether individual differences moderate the relationship between cue reactivity, craving and eating behavior as the number of published studies increases. This is especially important because some cross-sectional studies have demonstrated heightened cue reactivity in overweight individuals and restrained eaters (overweight: (1,41,218–220); restrained: (17,18,30,221)) as well as increased craving (19,64,222). Further, failure to detect differences based on dietary restraint measurements may be due to inconsistent and varied measurement of dietary restraint across studies (223–225) (Supporting Information). If cross-sectional differences in BMI and dietary restraint extend to predictive relationships with eating and weight gain, then food cue reactivity and craving could serve as markers of increased risk for restrained eating or becoming overweight.

In addition, some of the effects we detected may be due to small or imbalanced numbers of studies included in moderator-based analyses. For instance, we detected a stronger effect in mixed gender than female-only samples, contrary to the suggestion that females are more cue reactive (e.g. (226); Supporting Information). However, this comparison included almost double the number of mixed gender ($N_{STATISTICS} = 42$) compared with female-only statistics ($N_{STATISTICS} = 26$) and only one statistic in males. We hope that future studies will include more male-only and mixed-gender samples to further test for gender differences and will also test for any menstrual-cycle variations in females that may influence cue reactivity and craving. Similarly, we found that cue reactivity and craving were more strongly associated with long-term outcomes than short-term outcomes, which may also be attributable to an imbalanced number of studies (short-term: $N_{STUDIES} = 35$; long-term: $N_{STUDIES} = 10$). Future work could examine how far into the future the assessment of food cue responses and craving can predict outcomes and whether this is related to underlying trait-level individual differences.

Further, although a substantial literature suggests that appetitive conditioning increases, and depends upon, expectancy of reward (e.g. (227–231)), expectancy to eat did not affect the meta-analytic result (Supporting Information). Nevertheless, expectancy of food may be an important avenue for future work despite reported null effects on physiological reactivity to food cues (232), food craving (233) and food consumption (232,233).

Finally, given the parallels drawn herein between food and drug cue reactivity and craving, it may be useful to statistically compare these effects in future work. Notably, one prior meta-analysis of craving and cigarette smoking found similarly sized predictive effects ($rs = 0.20$–0.34) (121). Future meta-analyses should directly compare the predictive effects of cue reactivity and craving on cigarettes-related, drug-related and food-related outcomes.

Conclusions

Most people have an intuitive sense that wanting to eat a cookie increases one's chance of eating cookies. The present meta-analysis addressed this systematically by quantitatively examining the effects of food cue reactivity and craving on eating and weight-related outcomes. We found a medium-sized effect for all measures of food cue reactivity and craving on food outcomes, consistent with the 'cued overeating' model (8,9). We also found that reactivity to visual cues (pictures and videos) was as strongly related to outcome as reactivity to real food, which has important methodological implications. Our results parallel findings in the drug literature and suggest that these phenomena are cross-diagnostic and may have important clinical utility. This supports targeting food cue exposure and craving as part of obesity-

related public health interventions as well as clinical treatments for obesity, weight loss and eating disorders.

Conflict of interest statement

The authors report no conflicts of interest.

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