Laboratory-based interventions targeting food craving: A systematic review and meta-analysis

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Summary
This systematic review and meta-analysis aimed to quantify the effects of laboratory-based interventions targeting specific mechanisms of food craving, to identify moderators of effects, and to qualitatively summarize findings. The study was conducted and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Sixty-nine studies were included in the quantitative synthesis, and separate meta-analyses were conducted for the outcomes self-reported craving and objective food intake. Results show small to medium positive effects across specific craving interventions on both outcomes. Effect sizes were partly moderated by intervention type. The most effective intervention regarding food intake was in sensu cue exposure. For subjective craving, the most robust evidence was found for beneficial effects of cognitive regulation strategies (ie, reappraisal, suppression, and distraction). Results further indicate that training inhibitory control through behavioral inhibition might be more effective than approach-avoidance training when considering its effect on subjective craving and food intake. People with external eating habits, overeating, or loss-of-control eating might benefit from these types of specific craving interventions. Future research should focus on long-term effects, transferability, and effectiveness in clinical samples.

KEYWORDS
attentional bias modification, cognitive regulation, craving, cue exposure, food intake, inhibitory control training

1 | INTRODUCTION

Craving is defined as a strong and seemingly irresistible desire to consume a particular substance, such as a specific food or group of foods. Food craving not only is a core feature of bulimia nervosa (BN) and binge-eating disorder (BED) but is also found in nonclinical samples with external, emotional, or restrained eating and is related to overweight and obesity. A recent meta-analysis has shown that craving predicts food intake and weight gain with a medium effect size (ES). A high-powered study has furthermore shown that an early reduction in food craving is a reliable outcome predictor in pharmacological weight-loss trials.

Different theoretical models are useful to understand the emergence, generalization, pervasiveness, and urgency of craving. Thereby, both operant and respondent learning processes are of relevance, but also cognitive regulation and control, attentional deployment, and automatized behavior tendencies. The taste of food is known to be a primary reinforcer; thus, the rewarding properties of the intake of good-tasting food are learned by operant conditioning. Through association learning in the orbitofrontal cortex, the sight or smell of food...
can become a secondary reinforcer. Thus, craving can be elicited by a variety of cues in the environment, which is known as cue-induced craving and leads to a sensitization of associated brain circuits towards these stimuli. Through this process of “incentive sensitization,” associated cues become more salient and are processed with increased attentional resources. These attentional biases then contribute to the maintenance of craving and the appearance of disordered eating behaviors.

Contrary to conditioning models, the elaborated intrusion (EI) theory of desire states that externally triggered intrusive thoughts are only experienced as craving if the intrusion is cognitively elaborated. Accordingly, the genesis of craving is subdivided into two processing steps. First, intrusive thoughts are triggered by environmental cues, which are then followed by a cognitive elaboration process. This differentiation is relevant since interventions based on the EI theory of desire try to target the second processing step by interrupting the cognitive elaboration of cue-triggered craving. By contrast, interventions based on learning theories intervene on the first step by interrupting stimulus-response associations.

There is still the question of why some people may be more susceptible to cue-elicited craving and incentive sensitization than others. Here, interindividual differences in executive functions may come into play. It is known through cross-sectional and experimental studies that reduced inhibitory control is associated with higher craving, more loss of control over eating, and faster detection of food-related cues. Furthermore, people with problematic eating patterns show automatic action tendencies towards food, in that they react faster in response to food stimuli than to neutral stimuli when compared with healthy controls. Other studies have shown that people with higher craving have a comparably higher tendency to approach food cues and this approach bias is related to increased food intake. Therefore, in trying to modify craving and its effects on eating behavior, it appears to be important to target inhibitory control capacities, attentional deployment, and approach/avoidance behavior.

On the basis of these etiological models of craving, specific interventions addressing these different mechanisms of action have been developed to target craving. The first group of interventions tackling food craving appearing in the scientific literature involved cue exposure with response prevention, which is based on the classical conditioning learning theory. Learned associations between stimulus (eg, sight of food) and response (food intake) are sought to be uncoupled by extinction learning. Another group of interventions implement top-down control over craving through cognitive regulation strategies, including reappraisal, acceptance, suppression distraction, or imaginative techniques. A way to target the acquired salience of food stimuli is attentional bias modification (ABM), in which participants are implicitly taught to center their attention not on food stimuli, but rather on some kind of neutral stimulus, which is usually realized through modified dot-probe or antisaccade tasks. ABM tends to reverse incentive sensitization of food stimuli by reducing selective attentional processing of food cues; it usually targets very early attentional processes that may not easily be modified using top-down control strategies. Further interventions targeting executive functions include training to increase inhibitory control. This group of interventions often uses modified Go/No-Go or Stop-Signal tasks in order to train motor inhibitory control when confronted with food stimuli. Finally, neurofeedback and biofeedback training may increase different facets of self-regulation and thus be helpful for top-down control of craving.

In all these domains, a range of studies has been published, but there has been no systematic review or meta-analysis with regard to the effectiveness of interventions targeting food craving. While we know from recent meta-analyses that there are efficacious treatments for craving-related eating disorders, these treatments typically include a wide range of different interventions. Notably, it is usually difficult to infer specific mechanisms of action from randomized controlled trials that evaluate manualized treatment programs. This is especially the case when the modulation of one specific symptom (such as craving) is the focus of interest. Therefore, the present study explicitly aimed to evaluate treatments on the basis of specific mechanisms underlying craving, rather than treatment programs including various interventions. More specifically, the aims of this article were (1) to systematically summarize research with regard to interventions targeting either mechanisms of classically conditioned cue reactivity and/or enhancing top-down control over craving through cognitive, imagery-based, or behavioral training, (2) to quantify effects of craving interventions, and (3) to investigate possible moderators related to sampling and intervention characteristics.

2 | METHOD

This systematic review and meta-analysis was planned, conducted, and reported in accordance with the evidence-based Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

2.1 | Eligibility criteria

Eligibility criteria were defined as follows: (1) Study population: humans. (2) Interventions: (a) cue exposure with response prevention (in vivo, in sensu, or in virtual reality), (b) cognitive regulation strategies (ie, reappraisal, suppression, acceptance, and distraction), (c) training to modify cognitive control towards food cues (ie, ABM, food-specific inhibitory control training [ICT] such as modified Go/No-Go or Stop-Signal training, and approach/avoidance training [AAT]), and (d) biofeedback/neurofeedback training. (3) Outcomes: subjective food craving (experiential outcome measured through self-report) and food intake (behavioral outcome measured through direct energy intake). (4) Study designs: (a) clinical/randomized controlled trials with manipulation of interventions between-subjects design (BS-design) with n ≥ 10/group, (b) controlled crossover studies with manipulation of interventions within-subjects design (WS-design) with n ≥ 10, and (c) uncontrolled proof-of-concept studies measuring the effect of a manipulation pre-post design (referred to as PP-design) with n ≥ 20.
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The following interventions were excluded: unspecific, dietary (see Kahathuduwa et al. for a review), pharmacological (see Rebello and Greenway), exercise, noninvasive brain stimulation (see Lowe et al. and Sauvaget et al.), and bariatric surgery (see Myers et al.).

2.2 | Search strategy and study selection

Relevant studies were identified using the following electronic databases: Pubmed (688), PsycINFO (567), Medline (459), PSYNDEX (67), and Web of Knowledge (673). The reference lists of included articles were searched for more articles of interest. The last search was conducted on 05 March 2019 (see the supporting information for more information and a flow diagram [Figure S1] of the study selection process).

2.3 | Data extraction and preparation

The following data were extracted from the studies and summarized into tables: first author and year of publication, sample size, participant characteristics (Table S1: diagnoses, eating behavior, age, gender, and body mass index), intervention (type, number of sessions, and type of control intervention), means (M) and standard deviations (SD) of the primary outcomes food intake (Table S2), and craving (Table S3). For food craving, type of self-report measure (i.e., visual analogue scale/Likert scale asking for either “craving” or “desire to eat,” Food Craving (Chocolate) Questionnaire—State or Trait, and Craving Experience Questionnaire—State or Trait) and the respective scale ranges were additionally documented. Measures of food intake could be either a bogus taste test or free intake, it was quantified as the total amount of food consumed, reported in grams, kilojoules, or kilocalories, and if there were different types of food the mean for all foods offered in the taste test was used.

Studies were grouped into four intervention categories that were then further categorized into intervention types (cue exposure: in vivo, 3D/VR, and in sensu; cognitive regulation strategies: reappraisal, suppression, acceptance, and distraction; cognitive control training: ABM, ICT, AAT, and biofeedback/neurofeedback training). Further supposed moderators were sample type (healthy normal weight, overweight/obese, high [chocolate] craving), dieters/restrained eaters, [subclinical] BN, [subclinical] BED, and mixed sample/not specified), control type (no intervention/waiting list, sham control intervention, active control intervention—decrease, and active control intervention—increase), sample mean age, gender (percent female), and number of sessions. For the outcome craving, type of self-report questionnaire was included post hoc as an additional possible predictor for ES differences* (see the supporting information for more details regarding data extraction).

2.4 | Risk of bias and quality assessment

Assessment of the quality of each study was carried out using items A-F of the Effective Public Health Practice Project Quality Assessment Tool (EPHPP), along with two additional criteria regarding data analysis: a priori power analysis and quality/completeness of statistical data reporting. The following criteria were rated: selection bias, study design, confounders (differences between groups prior to intervention), blinding, collection methods, and dropout according to the EPHPP Dictionary. Studies received a total score of “strong” if there was no “weak” rating for any of these criteria, “moderate” with one “weak” rating, and “weak” if there were two or more “weak” component ratings. Statistical data reporting was rated as “complete” if the M and SD or standard errors were reported, as “sufficient” where available from graphs or sent upon request, and as “insufficient” if there were no data available for ES calculation and no response was received from the authors. Power analysis was rated with regard to whether it was done “a priori,” “post hoc,” or not done (“none”).

2.5 | Data synthesis

All studies for which ES calculation was possible were included in the quantitative synthesis. Studies for which ES calculation was not possible because of missing values were only included in the qualitative synthesis. For quantitative data synthesis, the standardized mean ES 

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g = \frac{M_{	ext{intervention}} - M_{	ext{control}}}{SD_{\text{within}}}\]

was calculated for each study outcome of interest for each of the individual studies. ES can be interpreted as very small (<0.15), small (±0.15 and <0.40), medium (±0.40 and <0.75), large (±0.75 and <1.10), very large (±1.10 and <1.45), or huge (±1.45). ES was calculated as the standardized mean difference between the active (A) and control (C) conditions measured postintervention: 

\[
d = (M_{	ext{intervention}} - M_{	ext{control}})/SD_{\text{within}}\]

in order to adjust for small sample size. ES was transformed to Hedges’ g for the statistical analysis using Bessel’s correction (see the supporting information for more details on data synthesis).

2.6 | Statistical data analysis

Statistical analyses were computed with RStudio version 1.2.5001 using the “compute.es” and “metafor” packages. Given the expected ES variation between studies, the meta-analysis was based on a random effects model using Hedges’ g. Estimated mean ES, its 95% confidence intervals (CIs), and its 95% prediction intervals (PIs) were calculated and tested for significance for both of the outcome variables separately. Assessment of inconsistency was carried out by calculating the I^2 value and its CI; this index of heterogeneity ranges from 0% to 100%, indicating low (25%), moderate (50%), and high (75%) heterogeneity. If heterogeneity was moderate or high, meta-regressions were calculated for the dummy coded (“psych” categorial variables study type (BS vs WS-design), intervention type (or, if type was nonsignificant, intervention category as a superordinate

*(Questionnaire type was not originally included as predictor but was added during the revision process. We would like to thank the reviewer for this important suggestion of including questionnaire type as an additional predictor into our regression models.)
intervention categorization), control type, sample type, and questionnaire type and for the continuous variables mean age, gender (% female), and number of sessions. Meta-regression analyses were based on mixed-effects models using restricted maximum likelihood estimation. Model significance was tested using F-tests; significance of regression coefficients was tested on a t-distribution using the Knapp-Hartung method that is recommended for random effects. For categorical variables, the most frequent category was used as the reference category. Using a forward selection process, predictors explaining heterogeneity in the first step were then introduced into multiple regression models. The Akaike information criterion (AIC) was used for model selection; lower values indicate a better model fit.

To assess for possible publication bias, asymmetry of funnel plots was visually inspected and Egger’s tests were calculated. Sensitivity analyses were conducted with regard to the effects of the exclusion of outliers. Outliers were detected in accordance with Viechtbauer and Cheung using the “metaoutliers” function of “altmeta”; studies are considered an outlier if the standardized residual is >3. Furthermore, adjusted ES was calculated using the trim and fill method described by Duval and Tweedie.

### 3 | RESULTS

#### 3.1 | Risk of bias and quality assessment

Overall, individual study quality was rated as “strong” in 32 studies, “moderate” in 22 studies, and “weak” in 25 studies (see Table S4). The main reasons for low study quality were no control/report of dropout and the use of unvalidated data collection tools (e.g., visual analogue or Likert scales). Some studies did not control for confounders (such as differences in state hunger between study groups) sufficiently, which was another reason for weak study quality ratings. Twenty-eight studies did not report on the statistical power of their experimental design, which may lead to bias because of insufficient power.

In the funnel plot for the outcome craving, a slight asymmetry towards higher positive effects in smaller studies was visible, but not significant ($P = .26$). In separate analyses for BS- and WS-design studies, no asymmetry was observed ($z < -0.06, P > .54$), and the trim and fill adjusted ES did not differ from the ES estimated from published studies. This was also true for the funnel plot of studies concerning food intake: Visually, it appeared that there was an asymmetry, whereby smaller studies had higher positive ES, but Egger’s test was not significant ($z = 1.17, P = .24$), and trim and fill analyses did not indicate an expected change in ES because of publication bias (see Figures S2-S4).

#### 3.2 | Main study findings

Altogether, 78 reports were included in the systematic review, of which 69 reports with 77 studies could be included in the quantitative synthesis; nine studies were included in the qualitative synthesis only. Most studies used healthy normal weight ($n = 7$) or convenience samples where health and weight were not specified ($n = 52$). Fifteen studies included overweight/obese samples, nine studies high (chocolate) crashers/disinhibited eaters, six studies restrained eaters or dieters, and six studies had (sub)clinical samples with BN ($n = 3$) or BED ($n = 3$). The majority of studies only included female participants ($n = 47$), with the remainder being mixed gender studies ($n = 41$). Participants were mostly adults; only five studies with children and three studies with adolescents were found (see Table S1).

### 3.2.1 | Food intake

For the food intake meta-analysis, 43 studies were included with 54 comparisons of effects, leading to a total of 1565 participants in active intervention conditions and 1570 control participants, plus 86 participants undergoing both conditions in a crossover design. Thirteen comparisons were categorized to the intervention category cue exposure ($n = 6$ in vivo and $n = 7$ in sensu) and 12 to cognitive regulation strategies ($n = 3$ acceptance, $n = 7$ reappraisal, and $n = 2$ distraction), and 29 comparisons were assigned to cognitive control training ($n = 16$ ICT, $n = 5$ AAT, and $n = 8$ ABM). No studies were found measuring food intake after neurofeedback or biofeedback training.

For the main analysis, a small but statistically significant summary ES of $g = 0.27$ (CI, 0.14-0.40; PI, −0.53 to 1.07; $P < .05$) was estimated, showing a small positive effect of craving interventions on the amount of food intake as compared with control interventions (see Figure 1). There was moderate to high heterogeneity in the observed ES ($I^2 = 71.21\%$; CI, 59.58-82.84). Therefore, a series of meta-regression analyses were calculated.

First, for the effect of study type, it was found that the cross-over study did not have a significantly different ES than studies with a randomized BS-design. Next, it was tested whether the potential moderators related to sample (gender, mean age, and sample type) and intervention characteristics (number of sessions, intervention type, and control type) explained any of the variance. While gender, mean age, sample type, and number of sessions did not explain any of the variance, control type and intervention type had some predictive value with intervention type explaining the largest amount of variability (see Table 1 for statistics). A multiple regression model with control type and intervention type as predictors was compared with the simpler model using only intervention type. Since the simpler model led to the better fit than the full model, the simpler model was retained. Intervention type significantly explained heterogeneity, leading to a residual heterogeneity of $I^2 = 63.79\%$ (CI, 47.72-79.20). T-tests showed that, compared with the reference intervention that was ICT with an estimated ES of 0.22, in sensu cue exposure had significantly higher effects ($B = 0.54, t = 2.58, P < .05$), while AAT tended to have smaller effects ($B = -0.36, t = -1.67, P = .10$). Reappraisal and ABM training had...
positive estimates (ie, tended to have higher effects than ICT), but t-tests were not significant (t-values ≤ 1.06, Ps ≥ .29), in vivo cue exposure, acceptance and distraction had lower ES than ICT, but these differences were not significant (t-values ≤ –0.38, Ps > .14).

3.2.2 | Food craving

For the outcome of craving, 52 controlled studies with 65 comparisons (35 randomized studies with n = 1140 in active groups and n = 1147...
TABLE 1  Statistical parameters for meta-regressions concerning the outcome food intake

| Predictor                       | F (df) | P Value | R² | AIC  |
|---------------------------------|--------|---------|----|------|
| Study type<sup>a</sup>          | 0.31(1, 52) | .58     | 0.00% | 83.94 |
| Sample characteristics          |        |         |     |      |
| Mean age<sup>b</sup>            | 0.31(1, 52) | .58 | 0.00% | 84.15 |
| Percent female<sup>b</sup>      | 1.06(1, 52) | .31 | 0.00% | 83.24 |
| Sample type<sup>c</sup>         | 0.69(6, 47) | .66 | 0.00% | 87.33 |
| Intervention characteristics    |        |         |     |      |
| Number of sessions              | 0.47(1, 52) | .50 | 0.00% | 83.84 |
| Intervention type<sup>d</sup>   | 2.64(7, 46) | <.05<sup>d</sup> | 27.54% | 77.03 |
| Control type<sup>e</sup>        | 1.95(3, 50) | .13 | 8.85% | 82.98 |
| Control type + intervention type| 2.01(10, 43) | .06 | 23.63% | 80.16 |

Note. Meta-regressions were calculated using a mixed-effects model; test statistics are computed using the Knapp-Hartung adjustment method and restricted maximum likelihood estimation.

Abbreviation: AIC, Akaike information criterion.

<sup>a</sup>Study type was coded as between- versus within-subjects designs.

<sup>b</sup>Missing values were imputed by the mean (for mean age four studies and for percent female two studies out of 54).

<sup>c</sup>Sample type was coded as follows: 1, healthy normal weight; 2, healthy overweight/obese; 3, high (chocolate) cravers; 4, dieters/restrained eaters; 5, bulimia nervosa (also subclinical); 6, binge-eating disorder (also subclinical); and 7, mixed sample/not specified.

<sup>d</sup>Intervention type was coded as follows: 1, in vivo cue exposure; 3, in sensu cue exposure; 4, reappraisal; 6, acceptance; 7, distraction; 8, attentional bias modification; 9, inhibitory control training; and 10, approach-avoidance training.

<sup>e</sup>Since intervention type was found a significant predictor, each intervention type was compared with the reference category "inhibitory control training."

3.3 | Sensitivity analyses

Sensitivity analyses were calculated with regard to the exclusion of outliers (see the supporting information for more details). For the food intake meta-analysis, one study was defined an outlier,93 exclusion of this study led to a slightly reduced but still significant ES for food intake. For WS-design studies with the outcome craving, there was an outlier in the reappraisal subgroup,93 which reduced the ES of reappraisal as intervention type and of the summary ES of this meta-
Since intervention type was found a significant predictor for within-subjects studies; each intervention type was compared with the reference category:

- 4, biofeedback/neurofeedback training.
- 5, suppression.
- 6, acceptance.
- 7, distraction.
- 8, reappraisal.
- 9, inhibitory control training.
- 10, approach-avoidance training.
- 11, biofeedback/neurofeedback trainings.

Within-subjects studies:
- For mean age one study out of 26).
- For percent female one study out of 41; for mean age three studies and for percent female one study out of 41; for within-subjects studies: for mean age one study out of 26).

Since there was a significant difference (within-subjects studies had higher effect sizes than between-subjects studies), separate meta-analyses and meta-regressions were calculated for the two study types.

Missing values were imputed by the mean (for between-subjects studies: for mean age one study out of 41; for within-subjects studies: for mean age one study out of 26).

Sample type was coded as follows: 1, healthy normal weight; 2, healthy overweight/obese; 3, high (chocolate) cravers; 4, dieters/restrained eaters; 5, binge-eating disorder; 6, mixed sample/not specified.

Intervention type was coded as follows: 1, in vivo cue exposure; 2, 3D cue exposure; 4, reappraisal; 5, suppression; 6, acceptance; 7, distraction; 8, attentional bias modification; 9, inhibitory control training; 10, approach-avoidance training; and 11, biofeedback/neurofeedback trainings.

Since intervention type was found a significant predictor for within-subjects studies; each intervention type was compared with the reference category:

- 4, biofeedback/neurofeedback training.
- 5, suppression.
- 6, acceptance.
- 7, distraction.
- 8, reappraisal.
- 9, inhibitory control training.
- 10, approach-avoidance training.
- 11, biofeedback/neurofeedback trainings.

Studies using single-item measures (ie, visual analogue scales or Likert scales) had higher effect sizes than studies using state questionnaires.

Questionnaire type was found a significant moderator, each subtype was compared with the reference category:

- Studies using single-item measures (ie, visual analogue scales or Likert scales) had higher effect sizes than studies using state questionnaires.

The results of the moderator analysis “percent female” indicate that studies with a lower percent of females had higher effect sizes. According to the model, studies with 50% females would have a mean effect size of $g = 1.12$, with each 1% more female participants; effect sizes would decrease by 0.01 point.

### TABLE 2  Statistical parameters for meta-regressions concerning the outcome subjective craving

| Predictor | F (df) | P Value | $R^2$ | AIC |
|-----------|--------|---------|-------|-----|
| Study type<sup>a</sup> | 20.71 (1, 65) | <.0001<sup>*</sup> | 39.43% | 89.22 |
| Between-subjects studies | | | | |
| Sample characteristics | Mean age<sup>b</sup> | 1.17 (1, 39) | .29 | 0.00% | 53.32 |
| Percent female<sup>b</sup> | 0.09 (1, 39) | .77 | 0.00% | 54.51 |
| Sample type<sup>c</sup> | | | | |
| Intervention characteristics | Number of sessions | 0.39 (1, 39) | .54 | 0.00% | 53.96 |
| Intervention type<sup>d</sup> | 1.34 (8, 32) | .26 | 8.00% | 56.61 |
| Intervention category<sup>e</sup> | 0.78 (3, 37) | .51 | 0.00% | 55.60 |
| Control type<sup>f</sup> | 1.15 (3, 37) | .34 | 8.15% | 54.68 |
| Questionnaire type<sup>g</sup> | 3.39 (3, 37) | <.05<sup>a</sup> | 26.77% | 48.13 |
| Questionnaire type + intervention category | 2.04 (6, 34) | .09 | 19.13% | 51.87 |
| Questionnaire type + control type | 2.07 (6, 34) | .08 | 21.51% | 51.90 |
| Within-subjects studies | | | | |
| Sample characteristics | Mean age<sup>b</sup> | 0.41 (1, 24) | .53 | 0.00% | 39.91 |
| Percent female<sup>b</sup> | 5.34 (1, 24) | <.05<sup>b</sup> | 39.04% | 36.25 |
| Sample type<sup>c</sup> | 0.59 (3, 22) | .63 | 0.00% | 40.76 |
| Intervention type<sup>d</sup> | 4.77 (2, 23) | <.05<sup>d</sup> | 52.21% | 34.84 |
| Control type<sup>f</sup> | 0.18 (2, 23) | .84 | 0.00% | 40.58 |
| Intervention type + percent female | 3.55 (3, 22) | <.05 | 51.95% | 35.69 |
| Intervention type * percent female | 2.52 (4, 21) | .07 | 46.99% | 37.24 |

Note. Meta-regressions were calculated using a mixed-effects model; test statistics are computed using the Knapp-Hartung adjustment method and restricted maximum likelihood estimation.

Abbreviation: AIC, Akaike information criterion.

<sup>*</sup>Study type was coded as between- versus within-subjects designs.

<sup>a</sup>Missing values were imputed by the mean (for between-subjects studies: for mean age three studies and for percent female one study out of 41; for within-subjects studies: for mean age one study out of 26).

<sup>b</sup>Sample type was coded as follows: 1, healthy normal weight; 2, healthy overweight/obese; 3, high (chocolate) cravers; 4, dieters/restrained eaters; 5, bulimia nervosa (also subclinical); 6, binge-eating disorder (also subclinical); and 7, mixed sample/not specified.

<sup>c</sup>Intervention type was coded as follows: 1, in vivo cue exposure; 2, 3D cue exposure; 4, reappraisal; 5, suppression; 6, acceptance; 7, distraction; 8, attentional bias modification; 9, inhibitory control training; 10, approach-avoidance training; and 11, biofeedback/neurofeedback trainings.

<sup>d</sup>Intervention category was coded as follows: 1, cue-exposure interventions; 2, cognitive regulation strategies; 3, cognitive control training; 4, biofeedback/neurofeedback training.

<sup>e</sup>Control type was coded as follows: 1, no intervention/waiting list control; 2, control/sham intervention; 3, active control intervention (with an attenuating effect on craving); 4, increase intervention (active intervention with a craving increasing effect).

<sup>f</sup>Type of questionnaire used for assessment of subjective craving was coded as follows: 1, state questionnaire; 2, trait questionnaire; 3, one-item measure (VAS/Likert scale); 4, mixed. Since questionnaire type was found a significant moderator, each subtype was compared with the reference category “one-item measure.” Studies using single-item measures (ie, visual analogue scales or Likert scales) had higher effect sizes than studies using state questionnaires for the assessment of food craving ($t = −2.78, P < .05$). Effect sizes of studies using trait questionnaires or different (mixed) measures for the assessment of craving did not significantly differ from studies using single-item measures ($t < 1.02, P > .32$).

### 3.4 Qualitative synthesis of studies excluded from the main analysis

With regard to food intake, one study showed a positive effect of a 2-week ICT for participants with overweight or obesity. A second study, where cue exposure training was compared with appetite awareness training, overweight children ate less snack food after eight sessions of cue exposure than after appetite awareness training. A study investigating the effects of distraction or acceptance on self-reported craving did not find the intervention effects to differ from the control condition. The fourth study investigated the effects of a six-session neurofeedback training and found a significant change on two subscales of the Food Craving Questionnaires—State and trait.
| Id - First author (Year) | N_A | N_C | Sample type | Hedges’ g [CI] |
|--------------------------|-----|-----|-------------|----------------|
| In vivo cue exposure     |     |     |             |                |
| 153 - Schyns (2016)      | 21  | 25  | Overweight  | 0.55 [-0.04, 1.14] |
| 160 - Van Gaucht (2008)  | 40  | 40  | Mixed       | 0.37 [-0.07, 0.81] |
| 108 - Coelho (2014)      | 11  | 12  | Mixed       | 0.14 [-0.64, 0.92] |
| 154 - Schyns (2018)      | 21  | 19  | Overweight  | 0.00 [-0.53, 0.71] |
| 116 - Frankort (2014)    | 17  | 17  | Normal weight| -0.56 [-1.27, 0.00] |
| 114 - Coelho (2014)      | 11  | 8   | Restrained  | -0.81 [-1.71, 0.00] |
| RE Model for Subgroup (QM = 0.01; p = 0.91; $R^2 = 58.1\%$) | | | | 0.02 [-0.38, 0.43] |
| Reappraisal              |     |     |             |                |
| 1441 - Moffitt (2012)    | 36  | 18  | Cravers     | 0.32 [-0.16, 0.80] |
| 192 - Vartanian (2016_1) | 64  | 63  | Mixed       | 0.32 [-0.04, 0.67] |
| 193 - Vartanian (2016_2) | 24  | 24  | Mixed       | -0.38 [-0.66, 0.11] |
| RE Model for Subgroup (QM = 0.20; p = 0.65; $R^2 = 67.0\%$) | | | | 0.10 [-0.34, 0.54] |
| Suppression              |     |     |             |                |
| 1012 - Alberts (2013)    | 20  | 11  | Mixed       | -0.62 [-1.55, -0.09] |
| Acceptance               |     |     |             |                |
| 1511 - Schumacher (2017_1) | 32  | 16  | Mixed       | 0.78 [0.16, 1.40] |
| 115 - Ferman (2013)      | 22  | 26  | Overweight  | 0.41 [-0.14, 0.96] |
| 1442 - Moffitt (2011)    | 38  | 18  | Cravers     | 0.47 [0.06, 0.88] |
| 1521 - Schumacher (2017_2) | 32  | 16  | Cravers     | 0.27 [-0.32, 0.86] |
| 113 - Fisher (2016)      | 20  | 20  | Mixed       | 0.06 [-0.45, 0.63] |
| 1011 - Alberts (2013)    | 20  | 10  | Mixed       | -1.23 [2.04, -4.23] |
| RE Model for Subgroup (QM = 0.44; p = 0.51; $R^2 = 76.0\%$) | | | | 0.16 [-0.32, 0.65] |
| Distraction              |     |     |             |                |
| 159 - van Dellen (2016)  | 31  | 32  | Mixed       | 0.75 [0.23, 1.27] |
| 1472 - Schmidt (2016)    | 18  | 11  | Bulimic     | 0.73 [0.03, 1.46] |
| 178 - Knäuper (2011)     | 25  | 18  | Cravers     | 0.51 [-0.11, 1.13] |
| 1522 - Schumacher (2017_2) | 33  | 16  | Cravers     | 0.23 [-0.36, 0.82] |
| 121 - Hamilton (2013)    | 34  | 15  | Mixed       | 0.20 [-0.26, 0.67] |
| 1512 - Schumacher (2017_1) | 30  | 16  | Mixed       | 0.03 [-0.56, 0.62] |
| RE Model for Subgroup (QM = 9.78; p = 0.00; $R^2 = 6.4\%$) | | | | 0.38 [0.14, 0.63] |
| Attentional bias modification |     |     |             |                |
| 133 - Kemps (2014_2)    | 44  | 44  | Mixed       | 0.52 [0.08, 0.96] |
| 150 - Schnitz (2017)     | 25  | 22  | Mixed       | 0.46 [-0.09, 1.01] |
| 106 - Bouteille (2014A)  | 15  | 15  | Overweight  | 0.46 [-0.25, 1.17] |
| 132 - Kemps (2014_1)    | 55  | 55  | Mixed       | 0.38 [0.00, 0.76] |
| 196 - Smith (2018)      | 25  | 50  | Overweight  | -0.00 [-0.45, 0.44] |
| 198 - Zhang (2018)      | 30  | 33  | Cravers     | -0.28 [-0.70, 0.14] |
| RE Model for Subgroup (QM = 2.69; p = 0.10; $R^2 = 51.4\%$) | | | | 0.23 [-0.05, 0.51] |
| Inhibitory control training |     |     |             |                |
| 124 - Houben (2015)     | 20  | 21  | Mixed       | 0.86 [0.04, 1.28] |
| 123 - Houben (2014)     | 16  | 19  | Mixed       | 0.07 [-0.56, 0.72] |
| 202 - Oomen (2018)      | 21  | 20  | Cravers     | -0.29 [-0.68, 0.00] |
| RE Model for Subgroup (QM = 0.25; p = 0.62; $R^2 = 58.1\%$) | | | | 0.14 [-0.41, 0.69] |
| Approach/avoidance training |     |     |             |                |
| 177 - Kemps (2013)      | 48  | 48  | Mixed       | 0.11 [-0.28, 0.50] |
| 195 - Werthmann (2014)  | 26  | 25  | Mixed       | -0.20 [-0.75, 0.35] |
| 111 - Ferentzi (2018)   | 64  | 65  | Overweight  | -0.29 [-0.63, 0.05] |
| 118 - Giel (2017)       | 10  | 10  | Binge-eating| -0.31 [-1.16, 0.54] |
| RE Model for Subgroup (QM = 1.31; p = 0.25; $R^2 = 12.5\%$) | | | | -0.14 [-0.39, 0.06] |
| Bio-/neurofeedback      |     |     |             |                |
| 1471 - Schmidt (2016)   | 18  | 10  | Bulimic     | 1.12 [0.31, 1.93] |
| 143 - Meule (2012)      | 14  | 14  | Cravers     | -0.06 [-0.71, 0.62] |
| 110 - Fattah (2017)     | 12  | 15  | Overweight  | 0.48 [-0.27, 1.25] |
| 148 - Schmidt (2017)    | 30  | 30  | Mixed       | 0.41 [-0.11, 0.93] |
| 149 - Schmidt (2015)    | 14  | 13  | Bulimic     | 0.04 [-0.69, 0.77] |
| 125 - Imperatori (2017) | 25  | 25  | Mixed       | -0.05 [-0.60, 0.50] |
| RE Model for Subgroup (QM = 5.89; p = 0.02; $R^2 = 26.3\%$) | | | | 0.39 [0.08, 0.71] |

**Random effects model**

QM = 6.91, p < 0.01, $R^2 = 51.64\%$ [33.23; 76.57]

Test of moderator intervention type:

F(3, 32) = 1.34, p = 0.26, $R^2 = 8.00\%$

**FIGURE 2** Forest plot for the outcome subjective food craving (between-subjects design studies) with random effects models for subgroups of different intervention types.

Note: Subgroups were compared in a meta-regression using intervention type as a dummy coded predictor. However, intervention type was not a significant predictor with $F_{0.32} = 1.34, P = .26$. AAT, approach-avoidance training; ABM, attentional bias modification; CE, cue exposure; CI, confidence interval; ICT, inhibitory control training; N_A, sample size active (intervention) group; N_C, sample size control (sham) group; RE, random effects.
3.4.1 Uncontrolled studies

There were five reports investigating the effect of different interventions in uncontrolled study designs (PP-design studies). One of these studies used AAT, two studies VR-/PC-operated cue exposure, and two studies cognitive regulation techniques. Since there were only seven comparisons in the PP-design category and these were of different interventions, no meta-analysis was calculated. A proof-of-concept study in bulimic participants showed large pre-post effects of a 10-session AAT on subjective craving. Two studies investigating cue exposure in virtual reality showed medium to huge pre-post ES on craving. A further study investigated a 7-day mobile intervention involving distraction and acceptance techniques on craving, both of which had large pre-post effects on self-reported craving. A study using suppression- and acceptance-based online self-help instructions did not have significant effects when comparing baseline with 2-week postintervention craving scores.

4 DISCUSSION

The aims of this article were to give a systematic summary of the literature regarding interventions to regulate craving in disordered and healthy eating behavior, to meta-analyze the effects of these interventions on craving and food intake, and to determine the influence of intervention- and sampling-related moderators. Separate meta-analyses were calculated for the outcomes food intake and subjective craving (craving studies were further divided into studies using WS-vs BS-designs due to methodological considerations).

Overall, this meta-analysis shows small but significant overall effects of laboratory-based interventions on subjective craving and food intake. Moderator analyses show that effects partly depended on the type of intervention used, the percentage of females included, and the type of questionnaire used to assess craving. For subjective craving, WS-designs had higher ES overall than BS-designs. This may be partly explained by reduced error variance in WS-designs, but could also be because all studies with WS-designs were coded to the same intervention category, namely, cognitive regulation strategies. Thereby, the highest effects on subjective craving were found for reappraisal and suppression; distraction led to significantly smaller effects compared with reappraisal.

With regard to food intake, the current evidence indicates that in sensu exposure to food cues might have the highest benefit; i.e., imagining the consumption of high caloric food might help to eat less when exposed to the same food. Importantly, all included studies regarding in sensu exposure were conducted by the same research group or were replications of these studies and all involved student populations whose weight and eating habits were not further defined. Therefore, as the study by Missbach et al showed that self-control resources are necessary for in sensu exposure to be effective, the effects should be investigated in people with problematic eating behavior, with weight/shape concerns, with low inhibitory control capacities and/or experiencing high craving. Another question regards ecological validity, since these studies were all conducted in controlled laboratory settings and effects might differ in settings that are more naturalistic.
Contrary to in sensu, in vivo cue exposure did not show a significant overall effect on food intake. One recent study, which found a null effect of in vivo cue exposure on food intake, also failed to find a supportive effect of an additive ICT to cue exposure. However, since some individual studies have suggested an effect of in vivo cue exposure on craving and food intake, duration and repetition of exposure might play a decisive role.

The largest number of studies with the outcome food intake was found in the domain of ICT. A small significant positive effect indicates that targeting control capacities towards food cues through ICT is effective in reducing food intake. Notably, AAT tended to increase food intake compared with control conditions, showing that current evidence does not point to a beneficial effect on food intake or craving for training that aims to increase avoidance of food stimuli. Importantly, ICT trials show positive effects especially with regard to food intake, while the effect is unclear with regard to craving. In contrast to AAT, which targets an early-situated cognitive control, ICT focuses on an improvement in late-stage motor-related inhibitory control. This suggests that it may be easier to train response inhibition as a late-stage controlled cognitive process (ie, through ICT) than to retrain more automatic approach biases (ie, through AAT). However, one study in which ICT and AAT were directly compared and combined found an additive effect of these interventions on implicit approach tendencies towards unhealthy food and healthier food choice after AAT. Yet neither intervention nor their combination had an effect on total food intake. Furthermore, most of the experimental studies were conducted in healthy samples; in a proof-of-concept study with subclinical BN participants, a 10-session AAT led to reduced self-reported craving. Moreover, a recent review reported positive effects of AAT with regard to the control of other appetitive cues (ie, alcohol and cigarettes). In the light of these findings, further investigation of AAT using multiple sessions and in subjects with problematic eating behavior and/or high craving is warranted.

As for distraction, there were small positive effects overall on subjective craving. For food intake, effects instead tended to be negative, but were only investigated in two trials. A possible mechanism of action of distraction is deduced from EI theory: Distraction might impede elaboration of cravings and thus lead to a reduction in the vividness of mental images. Both passive (eg, playing Tetris or spatial tapping) and active (eg, imagery and body scan) distractions seem to have a (at least short-term) positive effect on self-reported craving.

There are some limitations, which have to be borne in mind with regard to this meta-analysis. It is important to consider that the included studies used many different kinds of interventions, which were categorized according to predefined intervention types. However, not all studies coded as the same intervention type may have used exactly the same methodology, and thus, the categorization is somewhat artificial and might have led to a loss of information. The same applies to the moderators sample type and control type. Regarding sample type, most of the included studies were conducted with healthy normal weight participants or community samples; only six studies included participants with binge eating. More studies in clinical samples are needed to investigate moderation effects of symptom severity or trait craving. There was also a lack of studies with participants of lower or higher age. Moreover, some intervention types were investigated. Furthermore, mechanisms of action may be different in one-session regulation studies versus cognitive restructuring interventions. Notably, in most of the WS-design studies, participants were quite explicitly told what they are expected to do and craving was measured with regard to the same stimulus as participants were instructed to regulate. If, in contrast, application of the learned strategy and assessment of the outcome variable are decoupled, participants have to apply the learned strategies in their everyday life. This might lead to smaller effects of cognitive regulation, but also to higher ecological validity. The long-term effect and transferability of cognitive regulation strategies are therefore some of the most important topics for future research on interventions to reduce food craving.

The remaining studies in the domain of cognitive reappraisal used episodic future thinking (EFT). EFT teaches participants to imagine future events, which might lead to a change in perspective and was therefore coded as a type of reappraisal. An important influencing factor, however, might be whether the content of the EFT task is related to food or not. In fact, thinking about food-related topics led to less food intake and craving than thinking about non-food-related activities (eg, exercising). These results may indicate that the relevant mechanism of action in EFT studies is not necessarily related to future thinking, but to a type of in sensu cue exposure. Consequently, the mechanism of action in EFT might be food habituation rather than perspective change (see also previous literatures). Arguing against this, however, in previous EFT studies merely focusing thoughts on future events without thinking about food led to reduced food intake in obese children and adults. In this vein, a reduction in reward sensitivity may be a possible mode of action, another possible mechanism might be reinforcement of health-related goals through the EFT intervention.
represented by a low number of studies. This and limited precision of individual studies might partly account for unexplained heterogeneity.

Although, in line with the PRISMA guidelines, eligibility criteria and study questions were predefined in a review protocol, the protocol was not preregistered, which should be done in future studies so the research community has insight into the planning and realization of a review. Furthermore, although there were no statistically significant indicators, publication bias cannot be excluded. Visually, there was slight asymmetry in the funnel plots, which might indicate that studies with higher positive ES have a higher probability of publication than studies with negative ES. There may be unpublished data in the field, which were not considered in the current meta-analysis since only published studies were included and no attempts were made to detect unpublished studies (such as contacting researchers/professional societies in the field).

Limitations at the study level were assessed through a quality assessment tool. It showed that many studies did not control for or report dropouts, failed to control sufficiently for confounders, or used unvalidated data collection tools (eg, visual analogue or Likert scales). The use of these single-item measures might have led to an overestimation of effects (meta-regressions show differences in ES depending on type of measurement), which is problematic for reliability of results. Craving was mostly assessed subjectively through self-report, which may have led to socially desired answers (especially in studies with higher positive ES have a higher probability of publication than studies with negative ES. There may be unpublished data in the field, which were not considered in the current meta-analysis since only published studies were included and no attempts were made to detect unpublished studies (such as contacting researchers/professional societies in the field).

Limitations at the study level were assessed through a quality assessment tool. It showed that many studies did not control for or report dropouts, failed to control sufficiently for confounders, or used unvalidated data collection tools (eg, visual analogue or Likert scales). The use of these single-item measures might have led to an overestimation of effects (meta-regressions show differences in ES depending on type of measurement), which is problematic for reliability of results. Craving was mostly assessed subjectively through self-report, which may have led to socially desired answers (especially in crossover trials, where trials with and without the application of certain regulation strategies are compared, this risk is quite high). Furthermore, subjective craving does not always lead to pathological eating behavior such as binge eating. Therefore, it may be expedient to use more objective measures in addition to self-report, such as salivary reaction.

Furthermore, most studies conducted to date only involved a single intervention session and tested effects on craving and/or food intake immediately afterwards. Both clearly limit the clinical implications that can be drawn from these studies regarding the benefits of the respective interventions. In order to draw more meaningful clinical conclusions, studies should investigate whether participants are able to transfer the learned strategies into their everyday life. This could be done using mobile assessment methods such as ecological momentary assessment. Research should also increasingly focus on samples with clinically relevant eating disorders or other disorders affecting the regulation of food intake. In particular, individuals with binge-eating, external, or loss-of-control eating may benefit from treatments targeting the regulation of craving. Since obesity is a growing problem globally, is associated with serious health consequences, and high caloric food is omnipresent in our modern society, understanding the processes underlying the regulation of craving and developing appropriate interventions that can be easily applied and transferred to everyday life is essential.

In summary, this meta-analysis shows small but positive effects of psychological interventions on both subjective (self-reported craving) and objective (food intake) outcome measures. For food intake, the most effective intervention was in sensu cue exposure followed by reappraisal, with ICT also having a significant positive effect. For subjective craving, results differed depending on the study design, but overall cognitive regulation strategies (ie, reappraisal, suppression, and distraction) showed the most robust positive effects. Since there is evidence for a positive effect of ICT but not AAT on food intake, training inhibitory control through behavioral inhibition might be more effective than training avoidance of food stimuli.

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CONFLICT OF INTEREST

None declared.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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