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Review

The combined cognitive bias hypothesis in anxiety: A systematic review and meta-analysis☆

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ABSTRACT

Cognitive theories have postulated the relational nature of different cognitive biases in the development and maintenance of anxiety disorders. To test this combined cognitive bias hypothesis, this review addressed the following questions: (i) whether different cognitive biases are associated with each other and (ii) whether one bias influences another bias. We identified 36 articles that studied the relationship between cognitive biases (attention, interpretation and memory bias). Of these, 31 studies were entered into two meta-analyses. Sixteen studies were included in the first meta-analysis of the correlation between cognitive bias indices. A further 15 studies were included in another meta-analysis to examine the transfer effects of cognitive bias modification (CBM) to another bias. Both meta-analyses yielded small but significant overall pooled effect sizes after the removal of outliers ($r = 0.11$ and $g = 0.19$ respectively). Moderator analyses revealed that the relationship between interpretation and memory bias was significantly stronger than other types of cognitive bias correlations and CBM is more potent in modifying biases when it was delivered in the laboratory compared with online. Our review quantifies the strength of the relationships between biases and transfer effects following CBM, which serves as a basis to further understand the mechanisms underlying biased information processing.

1. Introduction

Anxiety disorders, the most prevalent mental disorders, are associated with immense distress and high burden on healthcare (Bandelow & Michaelis, 2015). Given the proposed role of cognitive bias in the development and maintenance of anxiety disorders (Beck & Clark, 1997; Mathews & MacLeod, 2005), there have been many cognitive studies in this research field since the 1990 s. Cognitive bias in anxiety refers to the preferential processing of threat-related information (Mathews & MacLeod, 2005; Williams, Macleod, & Mathews, 1997). Anxiety is suggested to modulate the processing of threatening stimuli, which increases the chance of confirming maladaptive or pathological beliefs. This in turn maintains anxiety symptoms. Attention, interpretation and memory biases are some of the major domains of cognitive biases that have been extensively studied.

1.1. The major domains of cognitive biases

Selective attention involves various aspects, including the process of orientation towards the location of attention, automaticity in allocating attention, and the capacity and ability to control attention (Yiend, 2010). Threat-related attention bias may manifest in several ways, such as facilitated processing of threat, difficulty in disengaging from threat and avoidance of attention from threat (Cisler & Koster, 2010; Cisler, Bacon, & Williams, 2009; Koster, Crombez, Verschuere, & De Houwer, 2004; Mathews & MacLeod, 2005). Attention bias towards threat among

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anxious populations is a relatively robust phenomenon, with one meta-analysis demonstrating a combined effect size of $d = 0.45$ (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007). Another meta-analytic review, specifically on eye-tracking methods, reported that anxious individuals show an increased vigilance for threat in both free viewing and visual search tasks. In that review the difficulty in disengaging from threat was mainly exhibited during visual search (Armstrong & Olatunji, 2012).

Interpretation bias refers to the tendency of resolving ambiguous information consistently in a negative or positive manner (Hirsch, Meeten, Krahé, & Reeder, 2016; Mathews & MacLeod, 2005). Interpretation involves various components, such as interpretation generation and selection (Blanchette & Richards, 2010). Anxiety can be associated with the differential generation of meaning from an ambiguous stimulus (Hertel, Brozovich, Joormann, & Gotlib, 2008; Taghavi, Moradi, Neshat-Doost, Yule, & Dalgleish, 2000) and with the preferential selection of mood-congruent meaning (Huppert, Pasupuleti, Foa, & Mathews, 2007; Klein, de Voogd, Wiers, & Salemink, 2018). Previous reviews reported that anxious adults (Hirsch et al., 2016) and children/adolescents (Castillo & Leandro, 2010) consistently demonstrated the tendency to resolve ambiguity negatively. The relationship between anxiety and negative interpretation in children and adolescents was supported by a meta-analysis which found a medium effect size (d =0.62) (Stuijfzand, Creswell, Field, Pearcey, & Dodd, 2018, pp. 12822).

Anxiety-linked memory bias is manifested by the selective memory of threatening information (Mathews & MacLeod, 2005; Mathews, Mogg, May, & Eysenck, 1989). According to Schacter (1992), there are two independent types of memory bias – implicit and explicit. Implicit memory refers to the unconscious recollection of previously learnt experience, which facilitates the performance of a task. Explicit memory, on the other hand, is the conscious or effortful recall of previously learnt information. Two meta-analyses reported evidence of anxiety-related memory bias for recall, with relatively small effect size of $d = -0.11$ (Mitte, 2008) and $d = 0.32$ (Herrera, Montorio, Cabrera, & Botella, 2017), respectively. However, both meta-anlayses showed no significant impact of anxiety on implicit memory bias. Mitte (2008) proposed that a memory bias in anxiety is most likely to occur when retrieval is constructive and related to top-down processes. Thus, when a task requires a low amount of constructive processing (e.g. implicit memory), the impact on memory is lower.

1.2. Prior reviews and research on the Combined Cognitive Bias Hypothesis

A central tenet of cognitive models of anxiety is the interrelationship *between* the cognitive biases involved in threat-related processing (e.g. Beck & Clark, 1997; Mathews & MacLeod, 1994). Hirsch, Clark, and Mathews (2006), among others, have used the term 'combined cognitive bias hypothesis' (CCBH), suggesting that cognitive biases influence and interact with each other. The combined operation of different types of cognitive bias is also proposed to have a proportionately greater impact on sustaining anxiety, compared to the additive contribution of each individual bias. An earlier review examined CCBH in depression and discussed the theoretical interplay of depression-related cognitive biases (Everaert, Koster, & Derakshan, 2012). They first identified three questions in studying CCBH:

(1) Association question – are different cognitive biases associated with each other,
(2) Causal question – does one bias influence another bias, and
(3) Predictive magnitude question – are biases independent or do they interact with each other in their association with depression?

The association question seeks to explore how cognitive biases at different stages of processing are related to each other. The causal question concerns the unidirectional or bidirectional influence of one cognitive bias on another bias. The prediction question focuses on how multiple cognitive biases in concert influence symptomatic presentation over a period of time (Everaert & Koster, 2020).

To our knowledge, no review to date has systematically investigated the relationship between different cognitive biases in anxiety. Similar to studies of depression, the current body of anxiety research can address the questions raised by Everaert et al. (2012). For example, some findings have demonstrated significant associations between attention and memory biases (LeMoult & Joormann, 2012; Reid, Salmon, & Lovibond, 2006) as well as between attention and interpretation biases (Richards, French, Nash, Hadwin, & Donnelly, 2007; Rozenman, Amir, & Weersing, 2014). Likewise, there is emerging evidence addressing the causal link between biases where manipulation of attention bias resulted in a change to interpretation bias (Bowler et al., 2017; de Voogd, Wiers, & Salemink, 2017) and vice versa (Amir, Bomyea, & Beard, 2010; Mobini et al., 2014). The pool of studies that evaluate the predictive magnitude question appears much smaller. Some evidence seems to suggest the independent contribution of cognitive biases on anxiety (Klein et al., 2014; Pergamin-Hight, Bitton, Pine, Fox, & Bar-Haim, 2016). However, the presence of null correlational and casual findings (e.g. Hoppitt et al., 2014; Teachman, Smith-Janik, & Saporito, 2007; Watts & Weems, 2006), also indicate that the evidence concerning this third question is inconsistent.

1.3. The present review and meta-analyses

In this review we focused on attention, interpretation and memory bias, using different criteria and analyses to address the first two questions identified by Everaert et al. (2012). First, to address the association question, we meta-analysed the correlation coefficients reported between different cognitive biases in pairwise combination. Second, to address the causal question, we examined studies using cognitive bias modification (CBM), the computerised procedure that aims to directly alter a specific cognitive bias to alleviate an associated psychopathology. If measures of other biases are included (i.e. those which are not targeted by the modification procedure), then this offers the opportunity to evaluate whether the modification of one bias type (e.g. attention) results in consistent changes to other types of bias (e.g. interpretation or memory). We therefore meta-analysed the reported transfer effects between CBM targeting one type of bias and post-CBM measures of other types of bias. We also conducted moderation analyses to examine the impact of the potential moderators on the association of cognitive biases and CBM transfer effects respectively.

1.4. Potential moderators

1.4.1. Bias-bias associations

Although the relationship between different types of cognitive bias is theoretically supported, it is unclear whether pairwise associations between different biases differ from each other. For instance, correlations between attention bias and interpretation bias may differ from those between attention and memory bias and so on. Quantifying the similarities and differences between different combinations of bias-bias association may elucidate how closely distorted cognitive processes coexist during information processing.

1.4.2. The pathway of transfer effects

Previous literature investigating CBM transfer effects proposed that active training (i.e. engaging in real time cognitive processing of the relevant emotional material during training) is key to eliciting transfer effects in subsequent assessment tasks (Hertel, Mathews et al., 2011; Hoppitt, Matthews, Yiend, & Mackintosh, 2010). According to Hertel, Mathews et al. (2011), successful transfer depends on whether the training and the subsequent task can invoke the same or similar cognitive process(es). There is abundant evidence that supports the "near transfer effect", whereby CBM effects transfer to other tasks with processing requirements similar to those being trained. Less consistent findings were found for "far transfer effects", which referred to the generalization of CBM training to more distal contexts. From our understanding of the current literature, little is known about the mechanism behind the transfer effect of CBM on a non-targeted cognitive bias because theoretically different cognitive processes are involved in the training and subsequent task. Thus, based on Beck's theory of negative cognitive schemas and the role of biases at various stages of processing in maintaining anxiety (Beck & Clark, 1997; Beck, Emery, & Greenberg, 1985), we hypothesised two possible routes through which CBM transfer effects on a non-targeted cognitive bias may occur.

The first one is an *indirect transfer pathway*, which occurs through the successful modification of the primary targeted cognitive bias (see Fig. 1). For instance, if the change of interpretation bias after attention bias modification (CBM-A) is significantly moderated by the successful modification of attention bias, then this would suggest that CBM-A had primarily modified attention bias (the targeted cognitive bias), and the corresponding alteration of interpretation bias (the non-targeted cognitive bias) would likely be due to its link with attention bias within a shared processing mechanism.

The second route is a *direct transfer pathway*, whereby the CBM manipulation has a direct effect on other non-targeted biases (see Fig. 1), independent of any effects on the targeted bias. For instance, if the successful modification of attention bias does not significantly moderate the change of interpretation bias after CBM-A, then we could infer that CBM-A had directly modified interpretation bias (the non-targeted cognitive bias) through the repeated training of altering attention bias (the targeted cognitive bias).

Of course, a third possibility is that transfer effects may occur via both routes simultaneously. In other words, CBM could exert direct effects on non-targeted biases, while at the same time having indirect effects through a cascading influence from one cognitive bias to another.

1.4.3. Stimuli matching

When assessing the relationships between different biases the degree of match between stimuli in the different tasks is an important consideration. For instance, it is common for studies to employ facial/pictorial stimuli to evaluate attention bias whilst using text-based assessments to measure interpretation bias (e.g. Lisk, Pile, Haller, Kumari, & Lau, 2018; Pergamin-Hight et al., 2016; Rozenman et al., 2014). In these studies, the stimuli used for each task are highly divergent and quite unrelated to each other, which might be expected to elicit weaker bias – bias associations. In contrast, another approach which adopts more similar stimuli across different bias tasks, could be expected to elicit stronger between-bias associations because variance associated with the stimuli themselves would be reduced. For instance, different types of text-based stimuli may be used in both attention and interpretation bias assessments (e.g. Reid et al., 2006; Teachman, 2005). The third approach seeks to reduce stimulus-driven variance even further by repeatedly using the same stimulus set for each bias task. Tasks are administered in a fixed temporal order (attention, interpretation, memory) reflecting the natural cycle of processing while utilising the same or similar stimulus materials throughout the experiment (Everaert & Koster, 2020). In this way, even a cross-sectional study design can be used to infer directional

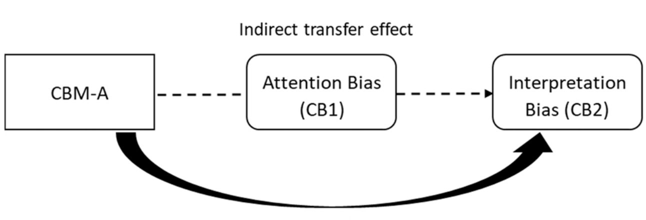

Fig. 1. The proposed pathway of CBM transfer effects.

relationships between sequentially administered cognitive bias tasks (e.g. LeMoult & Joormann, 2012; Lundh, Wikström, & Westerlund, 2001).

In the moderation analyses we considered the degree of match across stimuli sets used in the different bias tasks as a potential moderator. Similarly, the relatedness of the CBM training content and the subsequent cognitive bias assessment may also moderate the pooled efficacy of CBM in modifying the non-targeted cognitive bias. Based on the theoretical framework of transfer-appropriate processing (Blaxton, 1989; Morris, Bransford, & Franks, 1977), performance on memory test could be facilitated when the cognitive procedures invoked during the test was similar to those in the encoding process. Thus, in the context of CBM, a stronger transfer effect should theoretically be detected when there is a close match between the training content and the transfer tasks.

1.4.4. Characteristics of CBM

Among the two main types of CBM– CBM-A (focus on attention training) and CBM-I (focus on interpretation training), a recent review of meta-analyses reported that CBM-I appears to be more effective than CBM-A in evoking changes on the targeted bias, but both types of CBM are somewhat effective in reducing affective symptoms (Jones & Sharpe, 2017). Little is known about the transfer effect of CBM on a non-targeted cognitive bias. A moderation analysis investigating the impact of CBM type on transfer effects is therefore needed. Also, CBM is found to be most effective when delivered in the laboratory (Jones & Sharpe, 2017). But since the focus of these studies is mainly on anxiety symptoms or the targeted bias, further confirmation is required for the influence of delivery setting on transfer effects. These factors are thus included in the moderation analyses.

1.4.5. Sample characteristics

Studies often differ in sample characteristics. Most relevant here are age, type of anxiety disorder and symptom severity. Age has been found to moderate the link between threat-related bias and anxiety (Slavny, Sebastian, & Pote, 2019; pp. 2, 1282; Stuijfzand et al., 2018; pp. 2, 1282). This suggests that there may be important developmental changes that drive the manifestation of cognitive biases. Moreover, different anxiety disorders differ in terms of symptom manifestation, aetiology and prognosis (Bar-Haim et al., 2007). It is uncertain whether the relationship between different cognitive biases may be more reliably detected in a particular type of anxiety, suggesting type of anxiety disorder should be included as a moderator. Lastly, while it is reasonable to expect a stronger cognitive bias in participants with more severe pathology, it is unclear whether relationships between cognitive biases and CBM transfer effects differ according to anxiety severity. We therefore included these factors as potential moderators in our analyses.

1.5. Purpose of the review and potential implications

The purpose of the current study was to provide the first impartial summary of the relationship between different cognitive biases – attention, interpretation and memory biases in anxiety. The first objective was to assess the extent of empirical support for two types of bias-bias relationship - the association between biases and causal influences between biases. The second objective was to to determine the extent to which the suggested moderating factors exert an impact on bias-bias associations and the transfer effect of CBM on other cognitive biases.

Besides offering one rigorous way of resolving the inconsistent findings in the current CCBH literature in anxiety, our study has theoretical as well as clinical importance. Theoretically, it can test the reciprocal nature of cognitive biases in anxiety suggested by cognitive theories and models. The study of CBM can also elucidate the trajectory of cognitive processes in anxiety by investigating different possible pathways of transfer effects, as outlined above. The moderation analyses can inform researchers under what conditions are cognitive biases more likely to work in concert, and hence improve the methodology for studying biased information processing.

Clinically, the present study may contribute to a better understanding of the underlying mechanism of CBM. For instance, modification of attention bias may have solely resulted in symptomatic improvement, or it may have also altered other dysfunctional biases, such as interpretation and memory, which theoretically occur at later stages of processing. Moreover, meta-analyses have suggested that CBM may have little clinical significance due to its small effect size (Cristea, Kok, & Cuijpers, 2015; Liu, Li, Han, & Liu, 2017). By examining the potential factors that could moderate CBM transfer effects, it could inform researchers ways to maximise the effect of CBM and achieve symptomatic change. The present review is therefore important to enable researchers and clinicians to identify methodological issues in studying cognitive biases and the critical cognitive processes that underpin anxiety, which are essential in devising more effective interventions.

2. Method

2.1. Protocol and registration

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for reporting of this systematic review and meta-analysis (Liberati et al., 2009; Moher, Liberati, Tetzlaff, & Altman, 2009). Accordingly, the review was registered with PROSPERO [CRD42019142835]. Differences between the preregistered protocol and the current paper are outlined in Appendix E.

2.2. Identification and selection of studies

Following PRISMA guidelines a literature search was conducted on the electronic databases PubMed, Medline, PsycInfo and Web of Science, until October 2021. The following search terms were used: (((Information processing or cognitive bias or bias) and (attention* or interpret* or memory)) or (combined cognitive bias)) *AND* (Anxi*), ((cognitive bias modification or modif* or bias training) and (attention* or interpret* or memory)) *AND* (Anxi*). In addition, we contacted authors to request details of any further published studies and manually searched reference sections of relevant empirical articles, and previous reviews and meta-analyses (Cristea et al., 2015; Herrera et al., 2017; Liu et al., 2017; Mitte, 2008; Pergamin-Hight, Naim, Bakermans-Kranenburg, van IJzendoorn, & Bar-Haim, 2015) to identify any studies that had not been included in the literature databases. The initial search was conducted by independent researchers (CL and A Tse). Titles and abstracts were screened against the inclusion and exclusion criteria listed below by CL and A Tse, obtaining a high agreement in the screening process (kappa = 0.87). Full texts of potentially eligible studies were reviewed against the criteria by CL to determine whether they met the inclusion criteria of this review, with reference to senior authors JY and AT where there was any uncertainty. Any disagreements were resolved through discussion among CL, AT and JY.

2.3. Inclusion criteria

2.3.1. Types of cognitive bias assessment

Studies were included if they presented the association of cognitive biases – attention, interpretation or memory bias (Question 1); or modified one bias and assessed its effect on another bias (Question 2). There are various ways of conceptualising the paradigms of different cognitive bias measures (e.g. attention allocation versus attention control tasks, online versus offline tasks for interpretation bias, explicit versus implicit memory bias tasks). In the current meta-analyses, we conceptualised all cognitive bias tasks (attention, interpretation and memory biases) using the same method of classification to enhance uniformity in each construct. We took reference from recent reviews and meta-analyses (e.g. Everaert, Podina, & Koster, 2017; Field, Munafò, & Franken, 2009; Schoth & Liossi, 2017) on how different cognitive bias tasks were conceptualised and operationalized. Cognitive bias tasks are found to be commonly distinguished by how they are measured – direct and indirect measures. For direct measures, the outcome is based on participants' responses, such as their verbal or written response, or endorsement of a selection. For indirect measures, the outcome is based on participants' performance, such as response latencies instead of the participants' responses (De Houwer & Moors, 2010). Details about the definition and operationalisation of each cognitive bias are presented in the supplementary document.

In all types of study, the use of stimuli in the training or measurement of cognitive biases should be relevant to anxiety. For instance, the use of threat-related words (e.g. disabled, disease, foolish, harm) / threat facial expressions (e.g. disgust, anger). For studies focusing on specific anxiety disorders, the stimuli employed should be congruent with the disorder, e.g. socially relevant stimuli for social phobia or trauma-related stimuli for post-traumatic stress disorder. These study criteria are determined through literature review and review on articles listed in a previous meta-analysis that examined content specificity (Pergamin-Hight et al., 2015).

2.3.2. Types of participants

We included studies that assessed cognitive biases in patients presenting with clinically diagnosed anxiety disorders according to all versions of the Diagnostic and Statistical Manual of Mental Disorders (DSM) or International Classification of Diseases (ICD). We also included unselected samples or individuals presenting with subclinical anxiety symptoms, which in either case used a standardised instrument to measure anxiety traits/symptoms.[2]

2.3.3. Types of study design

Correlational studies which assessed the association between two or more cognitive biases were included in the review of Question 1. For experimental designs whereby cognitive bias was experimentally manipulated or modified, studies were included in Question 2 if participants were randomised and the effect of manipulation was compared to the effects of a control group or another active intervention. The cognitive bias being manipulated/modified should not be merged with another intervention.

2.4. Data abstraction and exclusion criteria

Data were extracted by CL and reviewed by JY and AT using a Microsoft Excel spreadsheet. We contacted the authors if any possibility of participant duplication between studies was identified. Details about the extracted data and exclusion criteria are presented in the supplementary document.

2.5. Quality assessment

To evaluate the quality of selected studies and reduce the impact of data selection in this review, risk of assessment bias was adopted by adapting the criteria from the Agency for Healthcare Research and Quality (AHRQ, 2014). The criteria (refer to Appendix A.1) included, i) selection bias; (ii) performance bias; (iii) detection bias; (iv) attrition bias; and (v) reporting bias. CL and A Tse rated the studies

[2] For studies which intended to recruit participants with subclinical anxiety symptoms, we checked the reported scores of the anxiety measurements before defining the samples as subclinical in our meta-analyses. For studies that recruited an unselected sample (i.e. had no inclusion criteria for the score of anxiety scales), we did not use validated cut-offs to define those samples because even though the reported average score may be above the cut-off, the SD may be large enough to include participants whose anxiety level was lower than the cut-off.

independently; any difference was resolved by discussion.

2.6. Planned methods of meta-analyses

Question 1. Meta-analysis on the association of cognitive biases.

Correlation coefficients were converted into a standard normal metric using Fisher's Z transformation. The results were then back-transformed into a pooled correlation coefficient r (Hedges & Olkin, 1985). As most of the retrieved studies provided multiple effect sizes (e.g. some effect sizes were obtained from the same sample), we conducted a three-level meta-analysis which allowed us to include multiple effect sizes within the same study in the analysis and avoid a decrease in statistical power due to the loss of information (Cheung, 2014; Hedges & Pigott, 2001). Details about the statistical plan of the multilevel meta-analysis and moderation analyses are presented in the supplementary document.

Question 2. Meta-analysis on CBM transfer effects.

As several cognitive biases were used for analysis, terminologies were defined below for clear illustration purposes. Primary targeted CB (CB1) refers to the cognitive bias, which was targeted for modification, e.g. attention bias in a CBM-A study. Secondary assessed CB (CB2) refers to the cognitive bias which was not the target of modification but was measured to assess the transfer effect of CBM, e.g. interpretation bias in a CBM-A study.

The standardised mean difference was calculated by subtracting, at post-test, the mean score of CB2 of the CBM group from that of the comparison group and dividing the result by the pooled standard deviation of the two groups. As only 5 out of 15 studies that were included in the meta-analysis reported multiple effect sizes, we decided to apply the conventional meta-analytic approach due to the difficulty in distinguishing the variances at the within-study and between-study level when most of the studies only have one effect size. Details about the statistical plan of the meta-analysis and moderation analyses are presented in the supplementary document.

3. Results

We identified 16003 articles through searching from various sources. After screening the titles and abstracts, 7578 articles were discarded. A sum of 1177 articles was rejected after reviewing the full texts. Fig. 2 presents the flowchart of the inclusion process and the detailed reasons for exclusion. Finally, a total of 36 articles were included in the current systematic review. Articles which did not report sufficient statistics for calculation of effect size were excluded from quantitative analyses. The most common missing statistics were the absence of correlation coefficients and the report of paired data only. We attempted to contact authors for the required statistics. We included 16 studies for the meta-analysis of the association of cognitive biases (Question 1) and 15 studies for the meta-analysis of CBM transfer effects (Question 2).

Question 3. Association between cognitive biases.

3.1. Characteristics of included studies

Studies included and their characteristics are summarised in Table 1. Seventeen studies fit into the inclusion criteria of the systematic review. Most studies reported more than one correlation coefficient, thus creating 36 coefficients in total. The three types of cognitive bias associations were – the correlation between attention and interpretation bias (16 coefficients), the association between attention and memory bias (12 coefficients) as well as the coefficients of interpretation and memory bias (8 coefficients).

All studies adopted a cross-sectional design. In terms of participant characteristics, 9 studies assessed cognitive biases in unselected/non-clinical samples only, 4 studies included clinical populations but used the whole sample when reporting the correlation between bias indices. Only 3 studies reported the correlation of bias indices in a clinical population and 1 study assessed a subclinical sample. Participants' mean age was 17.16 and the gender distribution on average was 64.54% female.

Most studies examined cognitive biases related to general anxiety (n = 8), 5 studied social anxiety, 2 studied panic, and another 2 were on spider phobia. The most common type of attention bias assessment was attentional cueing tasks in which attention is measured by the speed or accuracy of response (k = 22). Six other comparisons employed the word Stroop task. Interpretation bias was measured by the interpretation of ambiguous information in the form of words/vignettes (k = 7), facial expressions (k = 1) and questionnaires (k = 7). As for memory bias was measured by free recall (k = 15) and recognition tasks (k = 5). Less than half of the included studies (5 out of 17) had cognitive bias assessments sequentially related in stimulus content and matched in stimulus modality. For instance, if the facial stimuli used for an interpretation bias task is based on that employed in an attention bias task, the stimulus content of these two bias assessments are considered to be sequentially related and their stimulus modality (both being facial) are matched. (Refer to Appendix C for the detailed description of bias assessment tasks).

3.2. Quality assessment

The risk of bias ratings is shown in Appendix A.2. Out of the 17 studies, 15 were rated as good quality studies and 2 were classified as acceptable. The good quality studies satisfied all criteria listed on the risk of assessment bias. For the acceptable-quality studies, Pury (2002) intended to investigate whether pre-existing biases, as measured during a time of low stress, can predict emotional response to a real-life stressor. However, the authors did not include a screening assessment to ensure participants perceived the time of initial mood assessment to be a period of low stress. Ranđelović et al. (2018) missed providing the description of a questionnaire (STAI) in experiment 1 despite reporting its results. The inter-rater reliability before discussion was high (kappa = 0.75).

3.3. Meta-analysis

Sixteen studies (35 comparisons) were entered in the meta-analysis.[3] The overall analysis showed a combined effects size of $r = 0.14$ (95% CI: 0.0.038 to 0.238), indicating a small but significant correlation between cognitive biases in general. The estimated variance components were τ_2 (level 3) = 0.01 and τ_2 (level 2) = 0.02. Among the total variance, 55.09% and 26.74% could be attributed to between-cluster and within-cluster heterogeneity respectively. Constraining the within-study variance ($\chi^2 = 3.39$; $p = 0.065$) and between-study variance ($\chi^2 = 23.95$; $p < 0.001$) resulted in a deteriorated model fit, suggesting that the three-level model was favoured in estimating the pooled effect size.

One outlier/influential effect size was identified (Lundh & Öst, 1996). After the removal of the outlier, the overall effect size was still significant but dropped to $r = 0.11$ (95% CI: 0.027–0.184). Both inspection of funnel plot (Fig. 3) and the Egger's test showed that there was no significant publication bias ($b = 3.23$, $p = 0.594$). Out of all potential moderators, only the type of cognitive bias correlation was found to be significant, $F(2, 32) = 4.94$, $p = 0.014$, indicating that the relationship between interpretation and memory bias was significantly stronger than the other two types of cognitive bias correlations. This finding continued to be significant after the removal of the outlier. (Refer to Appendix B.1. for detailed results).

[3] (Teachman, 2005) was excluded from the meta-analysis because of insufficient data to calculate effect size.

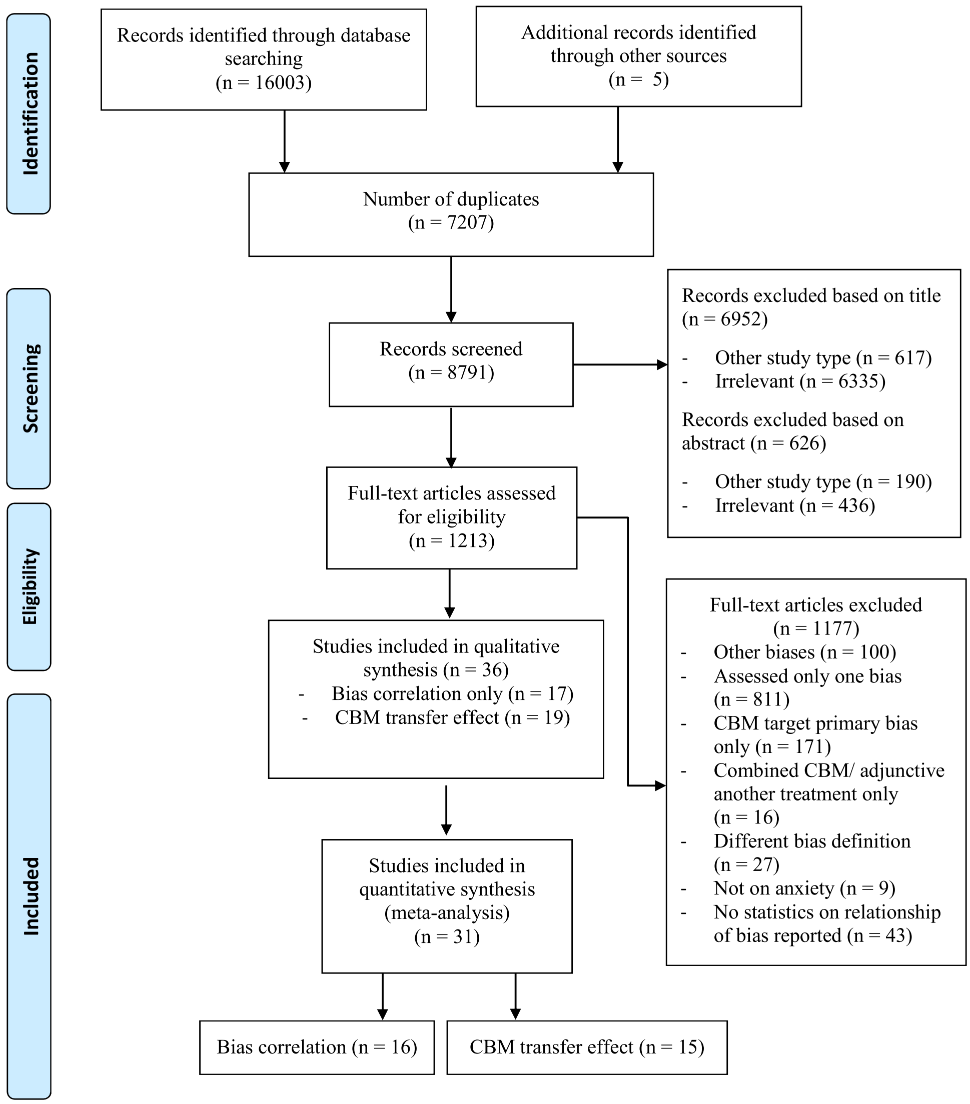

Fig. 2. Flowchart of the selection and inclusion process, following PRISMA guidelines.

Question 4. CBM transfer effects.

3.4. Characteristics of included studies

Study characteristics are summarised in Table 2. Among the 19 studies included, four studies (Bowler et al., 2017; Naim, Kivity, Bar-Haim, & Huppert, 2018; Yang et al., 2017; Yeung & Sharpe, 2019) measured the effects of both CBM-A and CBM-I with the same control group. One study assessed the impact of two types of CBM-A in two independent samples (de Voogd et al., 2016). One study contained two separate experiments (Hertel & Vasquez, 2011) while another study assessed attention bias with two types of tasks (de Voogd, Wiers, de Jong, Zwitser, & Salemink, 2018). Thus, there was a total of 26 comparisons in this systematic review.

In terms of participant characteristics, only 1 study used a clinical sample, 8 studies had subclinical samples, and the rest were unselected/non-clinical samples. Participants ranged from adolescents to adults. Their mean age was 20.74 and the gender distribution on average was 62.23% female.

All CBM studies found were either CBM-A or CBM-I. Nine comparisons assessed the effect of CBM-A on interpretation bias; 11 examined the effect of CBM-I on attention bias, and 6 measured the effect of CBM-I on explicit memory bias. The number of intervention sessions ranged from 1 to 8, with 14 studies only having one session. Seven studies delivered CBM online, while the rest were laboratory-based. Studies targeted modifying cognitive biases in either general anxiety (n = 9), social anxiety (n = 10). Most CBM studies aimed to train participants to process stimuli in a benign/positive direction, except 6 studies which included comparisons of negative training with either a control or benign/positive training group (Hertel & Vasquez, 2011; Hertel et al., 2014; Krans et al., 2019; Salemink et al., 2010; Tran et al., 2011; White et al., 2011).

Regarding the type of training paradigm employed in CBM studies, 6 comparisons used the modified version of the visual probe task and 3 used a visual search task for CBM-A studies. All of them used emotional faces as training stimuli, except for Bowler et al. (2017) and Yeung and Sharpe (2019) who used words. In CBM-I studies, the majority used scenario training (k = 13) while 4 used the Word Sentence Association Paradigm (WSAP). Out of all the studies, 7 studies did not include a baseline assessment of the target bias (CB1), which is essential for attributing post-intervention group differences to the action of CBM, rather than pre-existing group differences.

The most common assessment of attention bias was the attention cueing tasks (k = 15). Four comparisons measured preferential attention with the visual search task. Interpretation of ambiguous scenarios was used in the majority of interpretation bias assessment (k = 13)

Table 1
Systematic Review Study Characteristics (Correlational studies) (n = 17, k = 36).

Study	Meta-analysis	Sample (n)	CB i (measurement)	CB ii (measurement)	Targeted stimuli	Mean age	Gender (F) %	Relatedness of CB measures
Attention and Interpretation Bias								
Klein 2018	Y	Unselected sample (N = 659)	Attention bias (Visual probe task #)	Interpretation bias (SRT*)	Anxiety	14.40	59.20	Unrelated
Lisk et al. (2018)	Y	High social anxiety (SAS-A > 50) (N = 19)	Attention bias (Visual probe task*#)	Interpretation bias (AIBT*)	Social anxiety	17.03	94.74	Unrelated
Pergamin-Hight et al. (2016)	Y	SAD (n = 71) (DSM-IV diagnosis); Healthy control (n = 42)	Attention bias (Spatial-cueing Task #)	Interpretation bias (Ambiguous scenarios *)	Social anxiety	12.36	56.5	Unrelated
Pury (2002)	Y	Unselected sample (N = 29)	Attention bias (Stroop*)	Interpretation bias (Homophone interpretation task*)	Anxiety	no info	65.52	Unrelated
Reid et al. (2006)	Y	Unselected sample (N = 133)	Attention bias (Visual probe task*)	Interpretation bias (Ambiguous scenarios*)	Anxiety	11.04	45.83	Unrelated
Richards et al. (2007)	Y	Unselected sample (N = 50)	Attention bias (Stroop*)	Interpretation bias (Emotion expression task #)	Anxiety	11	52	Unrelated
Rozenman et al. (2014)	Y	Clinically anxious youth (DSM-IV diagnosis) (N = 26)	Attention bias (Visual probe task #)	Interpretation bias (WSAP*)	Anxiety	12.65	61	Unrelated
Teachman (2005)	N	Selected sample (ASI <14 OR >23) (N = 103)	Attention bias (Stroop*)	Interpretation bias (BBSIQ*)	Panic	18.9	66	Unrelated
Teachman et al. (2007)	Y	Panic disorder (n = 43) (DSM-IV diagnosis); Healthy control (n = 38)	Attention bias (Stroop*)	Interpretation bias (BBSIQ*)	Panic	35.54	61.5	Unrelated
Attention and Memory bias								
Klein et al. 2017	Y	Unselected sample (N = 81)	Attention bias (Stroop* #)	Memory bias (Recall of spider-related words*)	Spider phobia	10.2	68	Unrelated
LeMoult and Joormann (2012)	Y	SAD (n = 25), CMD (n = 15), Control (n = 33) (DSM-IV diagnosis)	Attention bias (Visual probe task #)	Memory bias (Facial recognition task #)	Social anxiety	24.33	57.37	Related
Ranđelović et al. 2018 (S1, S2)	Y	Unselected sample (S1 - N = 78) (S2 - N = 121)	Attention bias (Visual probe task #)	Memory bias (Free recall task*)	Anxiety	20.03 (S1) 19.8 (S2)	85.9 (S1) 85.1 (S2)	Unrelated
Reid et al. (2006)	Y	Unselected sample (N = 133)	Attention bias (Visual probe task*)	Memory bias (Levels of processing task – self-schema (free recall)*)	Anxiety	11.04	45.83	Unrelated
Watts and Weems (2006)	Y	Unselected sample (N = 81)	Attention bias (Visual probe task* #)	Memory bias (Word memory task*)	Anxiety	12.83	50	Related for word visual probe and memory task
Interpretation and Memory bias								
Field & Field 2013	Y	Unselected sample (N = 187)	Interpretation bias (Coded verbal response of threat or nonthreat interpretation*)	Memory bias (Coded verbal response of memory of the animal *)	Anxiety	10.07	62.03	Related
Lundh et al. 1996a	Y	SAD (DSM-III-R diagnosis) (n = 20); Healthy control (n = 20)	Interpretation bias (Rating of facial expression (quality of contact) #)	Memory bias (Facial recognition task #)	Social anxiety	32.25	80	Related
Lundh et al. 1996b	Y	SAD (DSM-III-R diagnosis) (n = 20); Healthy control (n = 20)	Interpretation bias (Rating of facial expression (critical/ accepting) #)	Memory bias (Facial recognition task #)	Social anxiety	31.75	90	Related
Parsons et al. 2021	Y	Unselected sample (N = 450)	Interpretation bias (AIBQ*)	Self-referential encoding task (free recall)*	Anxiety	13.37	55.11	Unrelated
Reid et al. (2006)	Y	Unselected sample (N = 133)	Interpretation bias (ambiguous vignette*)	Memory bias (Levels of processing task - self-schema (free recall)*)	Anxiety	11.04	45.83	Unrelated

Abbreviations Used: ASI – Anxiety Sensitivity Index; AIBT – Adolescent Interpretation Bias Task; BBSIQ - Brief body sensations interpretation questionnaire; CB – Cognitive bias; CMD – Comorbid; DSM – Diagnostic and Statistical Manual of Mental Disorders; IBQ – Interpretation Bias Questionnaire; SAD – Social Anxiety Disorder;

SAS-A – Social Anxiety Scale for Adolescents; SST – Scrambled Sentences Test; WSAP – Word Sentence Association Paradigm.
* = word stimuli; # = facial/ pictorial stimuli

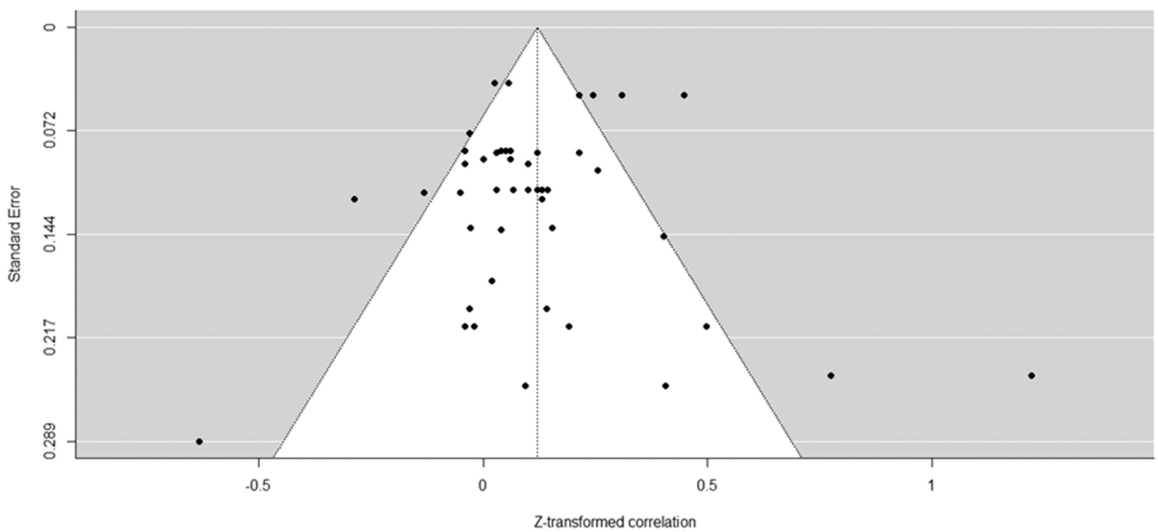

Fig. 3. Funnel plot of meta-analysis on the association between cognitive biases.

while 4 comparisons used WSAP. Besides experimental tasks, two comparisons adopted self-report questionnaires as indices of interpretation bias. For explicit memory bias, the tasks included in this review can be crudely divided into two types – the memory of scenarios and memory of interpretation. The memory of scenarios referred to tasks where participants were asked to actively recall factual details of previously presented scenarios (Salemink et al., 2010; Tran et al., 2011). The memory of interpretation, on the other hand, referred to participants' ability to recall the valence/interpretation of previously seen scenarios. In Hertel and Vasquez (2011); Hertel et al. (2014), participants were asked to recall how they have responded in situationally similar scenarios in the training phase and respond accordingly in new ambiguous scenarios. Similarly, Krans et al. (2019) assessed explicit memory bias based on the valence rating of the recalled memory. Due to the distinctive differences between these two types of memory tasks, it was inappropriate to include both of them in the same meta-analysis. As tasks that assess memory of scenarios are more similar to free recall tasks, which fit more closely to the inclusion criteria of previous meta-analyses on memory bias (Herrera et al., 2017; Mitte, 2008), we excluded Hertel and Vasquez (2011); Hertel et al. (2014) and Krans et al. (2019) from the subsequent meta-analysis. The training content of most CBM studies was not related to that of CB2, except those that assessed the transfer effect of CBM-I on memory bias (k = 5). In 14 comparisons, the stimuli used in CBM and CB2 were congruent in stimulus modality. (Refer to Appendix C and D for the detailed description of bias assessment tasks and CBM paradigms).

3.5. Quality assessment

As shown in Appendix A.2, a total of 10 studies were classified as good quality and the rest were categorized as acceptable. The most common reason for listing studies as acceptable was the absence of baseline assessment for the cognitive bias that was intended to be modified (Britton & Bailey, 2018; Hertel & Vasquez, 2011; Hertel et al., 2014; Salemink et al., 2010; Tran et al., 2011). This is crucial to ensure that participants are initially comparable in terms of their level of cognitive bias and determine the success of CBM. In addition, Birtton & Bailey did not include the post-intervention assessment of CB1, thus it could not be verified whether CBM was successful. Hertel and Vasquez (2011); Hertel et al. (2014), Salemink et al. (2010) and Tran (2011) did not report a complete sample demographics description. Two studies intended to recruit anxious participants but did not include a standardised screening assessment during recruitment (Bowler et al., 2017; Hoppitt et al., 2014). Two studies had less than 20 participants per group (Mobini et al., 2014; White et al., 2011). Mobini et al. (2014) did not include a section describing the general procedure of the study. The inter-rater reliability before discussion was moderate (kappa = 0.62).

3.6. Meta-analysis

One study (Britton & Bailey, 2018) did not provide sufficient information for the calculation of effect size. Including the exclusion of Hertel and Vasquez (2011); Hertel et al. (2014) and Krans et al. (2019) that was previously mentioned due to their distinctive task nature (memory of interpretation instead of the memory of scenarios/words), a total of 21 effect sizes from 15 studies were entered in the meta-analysis.[4] The overall results showed a small but significant combined effect size of $g = 0.22$ (95% CI: 0.112–0.336). Test of heterogeneity was non-significant ($Q(20) = 17.32$, $p = 0.632$, $I^2 = 0\%$). One outlier was identified (Tran et al., 2011). The removal of the outlier reduced the overall effect size to $g = 0.19$ (95% CI: 0.097–0.280) which remained significant. Heterogeneity was further reduced, ($Q(19) = 10.50$, $p = 0.940$, $I^2 = 0.0\%$).

As described earlier, five studies had either compared two CBM interventions with the same control group or used two measurements to assess the same cognitive bias. We, therefore, conducted two sensitivity analyses by including one effect size per independent sample. Inclusion of comparisons with only the largest effect size from each study resulted in a pooled effect size of 0.305 (95% CI: 0.173–0.434), heterogeneity was not significant ($Q(14) = 11.17$, p = 0.672, I2 = 0%). Whereas the pooling of smallest effect sizes yielded $g = 0.23$ (95% CI: 0.074–0.385) and heterogeneity of ($Q(14) = 15.62$, $p = 0.337$, $I^2 = 10.4\%$). Egger's test did not show evidence of significant publication bias ($b = 1.764$, $p = 0.139$). This was confirmed by the symmetry of the funnel plot (Fig. 4) and Duval and Tweedie's trim-and-fill procedure. As shown from Appendix B.2, the delivery mode of CBM was the only significant

[4] The bias score of Hoppitt (2014) visual probe task was obtained from imputation based on formula provided by the Cochrane Handbook (Higgins & Green, 2011).

Table 2
Systematic Review Study Characteristics (CBM Transfer effect studies) (n = 19, k = 26).

Study	Meta-analysis	Sample (n)	Manipulated CB [CBM paradigm] (measurement of CB1)	Delivery (no. of session & critical trials)	Success of CBM for CB1	Secondary targeted CB2 (measurement)	Age	Gender %	Relatedness of CBM and CB2 task
CBM-A on Interpretation bias									
Bowler et al. (2017) (C1)	Y	High anxiety (STAI-T = 48.40) (Training n = 22; Placebo control n = 24)	Attention bias [Visual probe training*] (Visual probe task)	Lab (8) (3072)	Y	Interpretation bias (SRT*)	19.14	68.18	Unrelated
Britton and Bailey (2018)	N	High social anxiety (LSAS-SR > 39) n = 42; Low social anxiety n = 47	Attention bias [Visual search training #] (no assessment)	Online (1) (112)	No baseline	Interpretation bias (ASSIQ*)	37.92	67.4	Unrelated
De Voogd et al. 2016 (S1 & S2)	Y	Unselected sample (VS Training (S1) n = 115, Placebo control n = 34) (VP Training (S2) n = 122; Placebo control n = 45)	Attention bias [Visual search training #, Visual probe training #] (Visual search and Visual probe task #)	Online (8) (VS – 1152; VP – 960)	Y (VS); N (VP)	Interpretation bias (SRT*)	14.41	59.76	Unrelated
De Voogd et al. 2017	Y	Highly anxious/ depressed (SCARED >16/ CDI >7) (Training n = 32; Placebo control n = 26)	Attention bias [Visual search training #] (Visual search task #)	Online (8) (1152)	Y	Interpretation bias (SRT*)	14.52	64.29	Unrelated
Naim et al. (2018) (C1)	Y	SAD (DSM-IV dx, LSAS ≥ 50) (Training n = 24; Placebo control n = 25)	Attention bias [Visual probe training #] (Visual probe task #)	Lab (8) (960)	N	Interpretation bias (SCT*)	31.02	44.9	Unrelated
White, Suway, Pine, Bar-Haim, and Fox (2011)	Y	Selected sample (STAI-Y ± 1 of normal range) (Training n = 14; Placebo control n = 15)	Attention bias [Visual probe training #] (Visual probe task #)	Lab (1) (600)	Y	Interpretation bias (SCT*)	20.8	100	Unrelated
Yang et al. (2017) (C1)	Y	High social anxiety (LSAS > 30) (Training n = 20; Placebo control n = 20)	Attention bias [Visual probe training*] (Visual probe task*)	Online (1) (640)	N	Interpretation bias (WSAP*)	21.23	65.79	Unrelated
Yeung and Sharpe (2019) (C1)	Y	High social anxiety (SIAS ≥ 15) (Training n = 30; Placebo control n = 32)	Attention bias [Visual probe training*] (Visual probe task*)	Lab (1) (320)	N	Interpretation bias (WSAP*)	19.07	77.42	Unrelated
CBM-I on Attention bias									
Amir et al. (2010)	Y	High social anxiety (LSAS-SR>25) (Training n = 29; Placebo control n = 28)	Interpretation bias [WSAP*] (Interpretation Questionnaire*)	Lab (1) (192)	Y	Attention bias (Spatial cueing task*)	19.5	53	Unrelated
Bowler et al. (2017) (C2)	N	High anxiety (STAI-T = 48.40) (Training n = 26; Placebo control n = 24)	Interpretation bias [Scenario training*] (SRT*)	Lab (8) (168)	Y	Attention bias (Visual probe task *)	18.96	57.69	Unrelated
De Voogd et al. 2017	Y	Highly anxious/ depressed (SCARED >16/ CDI >7) (Training n = 33; Placebo control n = 34)	Interpretation bias [Scenario training*] (SRT*, SST*)	Online (8) (240)	N	Attention bias (Visual search task #)	15.65	65.33	Unrelated
De Voogd et al. 2018 (E1 & E2)	Y	Unselected sample (Training n = 125; Placebo control n = 36)	Interpretation bias [Scenario training*] (SRT*)	Online (8) (240)	Y	Attention bias (Visual search task (E1) #, Visual probe task (E2) #)	14.35	60.7	Unrelated

(continued on next page)

Table 2 (*continued*)

Study	Meta-analysis	Sample (n)	Manipulated CB [CBM paradigm] (measurement of CB1)	Delivery (no. of session & critical trials)	Success of CBM for CB1	Secondary targeted CB2 (measurement)	Age	Gender %	Relatedness of CBM and CB2 task
Hoppitt et al. (2014)	Y	Unselected sample (Training n = 35; Placebo control n = 34)	Interpretation bias [Scenario training*] (SRT*)	Online (5) (130)	Y	Attention bias (Visual probe task*)	No info	55	Unrelated
Mobini et al. (2014)	Y	High social anxiety (FNE ≥ 17) (Training n = 19; No-training control n = 19)	Interpretation bias [Scenario training*] (SRT*)	Lab (1) (100)	Y	Attention bias (Visual probe task*)	24	73.5	Unrelated
Naim et al. (2018) (C2)	Y	SAD (DSM-IV dx, LSAS ≥ 50) (Training n = 23; Placebo control n = 25)	Interpretation bias [Scenario training*] (SCT*)	Lab (8) (95)	Y	Attention bias (Visual probe task #)	31.02	44.9	Unrelated
Yang et al. (2017) (C2)	Y	High social anxiety (LSAS > 30) (Training n = 20; Placebo control n = 20)	Interpretation bias [WSAP*] (WSAP*)	Online (1) (160)	Y	Attention bias (Visual probe task #)	21.23	65.79	Unrelated
Yeung and Sharpe (2019) (C2)	Y	High social anxiety (SIAS ≥ 15) (Training n = 28; Placebo control n = 32)	Interpretation bias [WSAP*] (WSAP*)	Lab (1) (248)	Y	Attention bias (Visual probe task *)	20.21	75	Unrelated
Zhang et al. 2021	Y	Self-reported social anxiety (Training n = 28; Placebo control n = 23)	Interpretation bias [WSAP*] (SCT*)	Lab (5) (550)	Y	Attention bias (Visual probe task *)	21.78	45.1	Unrelated
CBM-I on Memory bias									
Hertel and Vasquez (2011) (S1)	N	Selected sample (STAI-T < 39) (Negative training n = 16; Benign training n = 16; Control n = 16)	Interpretation bias [Scenario training*] (Time to complete fragments on probe trials*)	Lab (1) (60)	No baseline	Memory bias (Recollection and habit of responding negative resolution*)	No info	50	Related
Hertel and Vasquez (2011) (S2)	N	High anxiety (STAI-T > 39) (Benign training n = 20; Placebo control n = 20)	Interpretation bias [Scenario training*] (Time to complete fragments on probe trials*)	Lab (1) (60)	No baseline	Memory bias (Recollection and habit of responding negative resolution*)	No info	50	Related
Hertel, Holmes, and Benbow (2014)	N	Selected sample (STAI-T 34–47) (Negative training n = 24; Benign training n = 24; Control n = 24)	Interpretation bias [Scenario training*] (No assessment)	Lab (1) (80)	No baseline	Memory bias (Recollection and habit of responding benign resolution*)	No info	50	Related
Krans, Bosmans, Salemink, and De Raedt (2019)	N	Unselected sample (Pessimistic training n = 60; Optimistic training n = 60)	Interpretation (expectancy) bias [Scenario training*] (SRT*)	Lab (1) (64)	Y	Memory bias (Valence of autobiographi-cal memory)	20.12	84.17	Unrelated
Salemink, Hertel, and Mackintosh (2010)	Y	Unselected sample (Positive training n = 37; Negative training n = 38)	Interpretation bias [Scenario training*] (SRT*)	Lab (1) (64)	No baseline	Memory bias (Intrusions in scenario recall*)	No info	74.67	Related
Tran, Hertel, and Joormann (2011)	Y	Unselected sample (Positive training n = 29; Negative training n = 29)	Interpretation bias [Scenario training*] (SRT*)	Lab (1) (80)	No baseline	Memory bias (Number and valence of memory intrusions*)	No info	48.28	Related

Abbreviations Used: ASSIQ – Ambiguous Social Scenarios Interpretation Questionnaire; CB1 – Primary targeted cognitive bias; CB2 – Secondary assessed cognitive bias; CDI – Children's Depression Inventory; DSM – Diagnostic and Statistical Manual of Mental Disorders; dx – diagnosis; FNE – Fear of Negative Evaluation Scale; LSAS-SR – Liebowitz Social Anxiety Scale – Self report measure; SAD – Social anxiety disorder; SCT – Sentence Completion Task; SCARED – Screen for Child Anxiety Related Emotional Disorders; SIAS – Social Interaction Anxiety Scale; SRT – Similarity Ratings Task; SST – Scrambled Sentences Test; STAI – State-Trait Anxiety Inventory; WSAP – Word Sentence Association Paradigm; VS – Visual search; VP – Visual probe.
* = word stimuli; # = facial stimuli

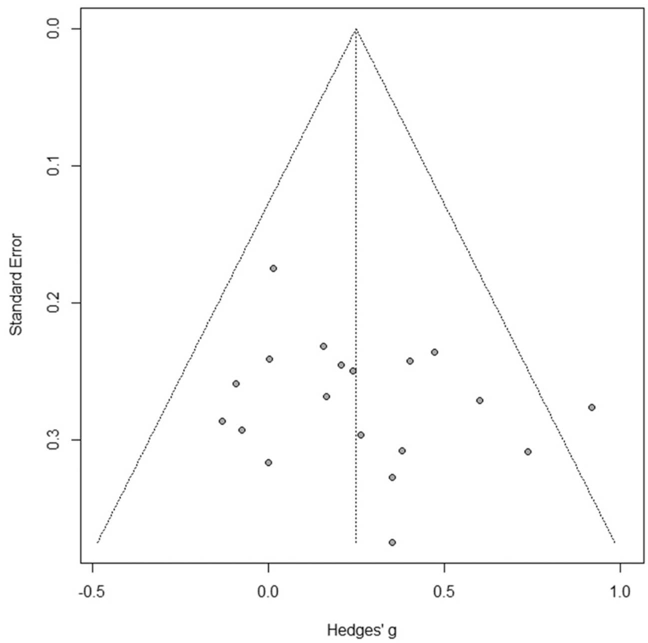

Fig. 4. Funnel plot of meta-analysis on CBM transfer effect.

moderator. CBM delivered in a laboratory setting was found to have significantly higher effect sizes than CBM delivered online ($p = 0.043$). This finding was no longer significant after the outlier was removed ($p = 0.106$).

4. Discussion

4.1. Summary of main findings

We conducted the first systematic review and meta-analysis on the relationship of cognitive biases (attention, interpretation and memory bias) in anxiety. Overall, the present findings provide broad support for the CCBH by showing small but significant relationships between cognitive biases, both in terms of correlations ($r = 0.11$) and transfer effects following CBM training ($g = 0.19$). There was low to medium heterogeneity of the pooled effect sizes. Several a priori identified moderators related to theory and methodology were examined to determine the sources of heterogeneity. The current meta-analyses did not indicate the presence of publication bias. However, we should interpret the findings with caution due to the small pooled effect sizes.

4.2. Moderators of bias-bias association and CBM transfer effect

4.2.1. Bias-bias associations and the pathway of transfer effects

In this meta-analysis, the findings suggested that the relationship between interpretation and memory bias might be stronger than the other two types of cognitive bias correlations (i.e. AB and IB, AB and MB). With reference to Beck's theory of schema-based processing (Beck & Clark, 1997), attention bias is generally assumed to operate automatically at the early stage of information processing. Interpretation and memory biases, on the other hand, both occur at the later stages of processing, which involve strategic regulation and controlled processing. It is plausible that interpretation and memory biases might be more closely related because the respective bias measurements allowed more elaborative and reflective thinking, which consciously activated schemas related to participants' personal concerns, resulting to more congruence and stronger associations between these two biases.

We had hypothesised that CBM transfer effects might occur through two possible pathways – the direct and indirect pathways. Our subgroup analysis showed that the successful modification of CB1 was not a significant moderator of the overall transfer effect. Thus, we suggested that there might be little support from our analysis for the first route. This was in line with the results of our first meta-analysis. Given the weak correlation between cognitive biases, the successful modification of CB1 might not be strong enough to alter CB2. The observed transfer effects might therefore primarily be driven by the second route – the direct action of CBM upon non targeted biases, instead of a cascading influence from one cognitive bias to another. With reference to theories of information processing (e.g. Ingram, 1984; Schneider & Shiffrin, 1977), the mechanism for direct transfer possibly involves the automatic and efficient processing of content-congruent information that is activated by a learned sequence of elements in long-term memory. The repeated and active preferential processing of one category of information (e.g. attending to benign over threatening information) during CBM likely induced an implicitly learned production rule (Hoppitt et al., 2010), which directly modified related cognitive processes (e.g. interpretation bias) during the subsequent processing of same-category information.

4.2.2. Stimuli matching

Findings of our meta-analyses suggested that relatedness of stimuli across bias assessment and training might not influence bias association and CBM transfer effect. However, less than half of the included correlational studies used cognitive bias assessments which were sequentially related and matched in stimulus modality and content. Thus, there was insufficient data to inform how emotional material is modulated by various biases across different stages of information processing. This might also have explained the weak relationship between cognitive biases obtained in this review. Functional imaging studies provide evidence that words and faces engage separate neural mechanisms. The Visual Word Form Area (VWFA) responds exclusively to visually presented words and letter strings, while the Fusiform Face Area (FFA) is selectively activated by faces (Plaut & Behrmann, 2011). Thus, the use of matching stimulus content and modality across bias assessments increases the likelihood of the same neuronal network being used for processing. Theoretically, the association between measurements of how the same facial stimuli are being attended to and interpreted should be stronger than the correlation between attention to faces and interpretation of unrelated text-based scenarios. Likewise, only three of the CBM studies had related content in the CBM training and subsequent secondary cognitive bias task. In line with the concept of transfer in memory research (Blaxton, 1989; Godden & Baddeley, 1975), the strength of transfer effects, in general, is thought to depend upon the close match between the cognitive processes, context and stimulus material used in both the training and transfer tasks. Thus, the independent content of training and bias tasks in some of the reviewed CBM studies could have contributed to the weak transfer effects found.

4.2.3. Characteristics of CBM

Despite the differences between CBM-A and CBM-I, the non-significance of CBM Type in the moderation analysis suggested the potential equivalence of both CBM approaches in modifying non-targeted bias. Evidence demonstrating the transfer effect of CBM in influencing both upstream (e.g. CBM-I on attention bias) and downstream (e.g. CBM-A on interpretation bias) processing provided further support for the bidirectional relationship of cognitive biases, suggesting that early effects of threat on attention may produce knock-on effects on higher level of cognitive functioning and that strategic processing, in turn, shapes attention deployment.

Subgroup analysis revealed CBM to be more potent for bias change when it was delivered in the laboratory compared with online, which aligned with findings from previous meta-analyses (Jones & Sharpe, 2017). It was likely to be due to the ease of implementation in standardised conditions and the reduction of distractions in the laboratory, which in turn led to smaller error variances on most measures. Online testing is subject to the 'real-world' environment which is well known to increase error variance due to non-standard conditions. The challenge for CBM research will be to decrease such error variance because the online platform is needed for any widespread clinical application of CBM techniques.

4.2.4. Sample characteristics

Clinical status was not a significant moderator for both meta-analyses, suggesting that the relationships between cognitive biases and CBM transfer effects might not differ according to anxiety severity. This was in line with the findings of previous meta-analyses that anxiety level has no significant impact on the magnitude of cognitive biases (e.g. Bar-Haim et al., 2007; Mitte, 2008) nor the efficacy of CBM transfer effect (Jones & Sharpe, 2017). Contrary to our expectation, age and the type of anxiety did not moderate the overall effect, suggesting that bias association and CBM transfer effect might be similar across developmental course and anxiety spectrum.

4.2.5. Other factors that influenced the findings

Two other factors might have contributed to the weak relationship observed among cognitive biases and might qualify our conclusions. Firstly, there is criticism of the reliability, and hence validity, of some bias measurements. For example, attentional bias has received considerable criticism both in terms of its efficacy as a bias modification procedure (Cristea et al., 2015) and in terms of measurement properties as a test of naturally occurring bias, including poor internal consistency and test-retest reliability of typical attention bias measures (Macleod, Grafton, Notebaert, & Rutherford, 2019; Schmukle, 2005). There are also suggestions that CBM-A may be changing attentional control instead of attention bias per se (Heeren, Mogoaşe, McNally, Schmitz, & Philippot, 2015; Mogg, Waters, & Bradley, 2017). Mogg et al. (2000) and Dalgleish et al. (2003) administered both Stroop and visual probe tasks to a sample of sub-clinically and clinically anxious individuals respectively. Both of them found no significant correlations between the bias indices generated from these two tasks. Given bias measurements that were designed to tap the same cognitive bias could yield inconsistent results, our finding of small inter-bias correlation was not entirely surprising. Secondly, as the main aim of our review was to ascertain whether cognitive biases are empirically associated, we included all types of bias correlations and CBM in the two meta-analyses. It was possible that such combination of findings increased heterogeneity in our analyses and correspondingly weakened effect sizes.

4.3. Implications and recommendations

The present findings broadly supported the proposed relationship among cognitive biases in CCBH. The significant correlations between cognitive biases and bidirectional transfer effects between CBM-A and CBM-I provided support to the notion that attention, interpretation and memory biases are not independent cognitive mechanisms, and they likely stem from a shared underlying mechanism in anxiety (Beck & Clark, 1997; Mathews & MacLeod, 2005). Our findings about the associations between cognitive biases in anxiety are largely consistent with the empirical evidence demonstrated in the depression literature (e.g. LeMoult & Joormann, 2012; Sanchez, Duque, Romero, & Vazquez, 2017). However, unlike our findings in anxiety studies, there is currently a lack of support for bidirectional influences between attention and interpretation biases in depression (Everaert & Koster, 2020). Future research is needed to elucidate whether such difference is related to methodological reasons or whether it represents a distinctive feature between anxiety and depression. Moreover, we should interpret the present meta-analyses findings with caution in view of the small pooled effect sizes. Although the typical effect sizes obtained in experimental assessments of cognitive biases and CBM are known to be small (Bantin, Stevens, Gerlach, & Hermann, 2016; Jones & Sharpe, 2017), it is possible that the small effects we report could disappear when more studies are included in the future, leading to different conclusions.

Nonetheless, the results of this review may shed light on the future advancement of CCBH research. Although cognitive biases are found to be related to each other, there is currently a lack of empirical investigations on how anxiety-related cognitive biases work in concert during information processing. One way of addressing this in future would be to examine all three biases in a single study. Several depression studies have done this, demonstrating the indirect effect of interpretation bias on the relationship between attention and memory biases, suggesting that attentional deployment to negative information might be a factor associated with selective memory through biased interpretation (Everaert, Duyck, & Koster, 2014; Everaert, Tierens, Uzieblo, Koster, & Dunantlaan, 2013; Sanchez et al., 2017). In our current meta-analysis, only one study examined all three cognitive biases in anxiety (Pury, 2002). As that study utilised unrelated cognitive tasks, it was difficult to draw conclusions regarding the interplay of cognitive biases in anxiety. In addition, most studies to date have examined the impact of attention bias during encoding of emotional material to explain memory bias. Little is known about the other relationships, such as the influence of memory bias in shaping attention and interpretation bias in either depression or anxiety. Thus, we urge researchers to study these processes in an integrative manner to further our understanding of the mechanisms that underpin anxiety-linked cognitive biases.

Clinically, as CBM may modify both targeted and related biases, more studies are needed to directly compare the therapeutic effects of different CBM approaches. Currently, only three studies were found to examine the relative efficacy of CBM-A, CBM-I and combined CBM (Naim et al., 2018; Yang et al., 2017; Yeung & Sharpe, 2019). While all of them found single CBM to be more effective, two studies lent support to the relative efficacy of CBM-I and the other study substantiated the effect of CBM-A. These studies also have several distinct methodological differences, such as the number of training sessions, the delivery mode and the training method of CBM. Further investigation is needed to evaluate the relative efficacy of single and combined CBM. Moreover, as the association between interpretation and memory biases was found to be stronger than the other two types of cognitive bias correlations (i.e. AB and IB, AB and MB) in our meta-analysis, it is plausible that simultaneously targeting interpretation and memory biases might attain stronger transfer effects on cognitive biases, compared to the combined effect of CBM-A and CBM-I. More studies are warranted to tailor optimal CBM interventions to maximise symptomatic improvement.

We suggest future research should also take note of the following methodological considerations in studying CCBH. Firstly, paradigms should be designed to specifically investigate the relationship between multiple biases, rather than examining this as a secondary aim or in a post hoc manner. Secondly, these designs should be carried out in laboratory settings to ensure effect sizes are not compromised by uncontrolled error variance. Thirdly, there is much variation in the paradigms used to measure a given construct (e.g. attention bias can be measured by the dot probe task, visual search task and many others). Findings regarding the relationship between cognitive biases could differ depending on the paradigm used. We therefore recommend future studies should test the moderation effect of paradigm type. Fourthly, stimuli employed across different types of bias measurements should be directly related to each other and matched in content and type (text, face, pictorial etc.). Not only is this important in substantiating the theoretical role of how various cognitive biases interact in the processing of emotional information, but it also ensures optimum conditions for transfer effects to be observed. By comparing protocols which utilise both closely matched as well as more distinct stimulus types, researchers could quantify the maximum transfer effect sizes under optimum conditions, in contrast to those more likely to occur in real-world settings.

4.4. Limitations

First, we only investigated CCBH in attention, interpretation and memory biases. Although less studied, there are other biases such as expectation and perception bias, which may also play an important role in further understanding the interplay of cognitive biases. Given the complexity of the information processing system, future studies may delineate CCBH by considering more cognitive biases. Second, cognitive processes are multi-faceted with different components. Findings in this review are therefore only applicable to the current narrow definition of cognitive bias. Third, although a large number of studies investigated more than one cognitive bias most of them were not included in our correlation meta-analysis because no relevant correlation coefficient was reported, and the data were not publicly available for retrospective calculations. It was also uncommon for CBM studies to assess cognitive biases other than the ones that were targeted for modification. Therefore, only a fraction of studies initially identified fitted into our inclusion criteria. The number of effect sizes included was small and this is a limitation of the current study.

In addition, we had to group studies together despite variations among their cognitive bias measurements. For instance, free recall and recognition tasks were grouped under the category of explicit memory bias when studying its relationship with other cognitive biases due to the small number of studies. We acknowledged that the lack of uniformity in task paradigms might potentially affect our statistical power. We thus attempted to increase study consistency in our meta-analyses by maximising the comparability of bias indices where possible. For example, we chose only supraliminal indices for attention bias measures and only memory of factual information as indices of memory bias in CBM studies.

Other limitations exist in our review. The processes of article screening and data abstraction were mainly done by the first author (CL) and thus, our work was subject to possible selection bias and the risk of accidental study omission. However, when in doubt, the first author (CL) sought advice from senior academics (JY and AT) to ensure the quality of the process. Also, we only included published articles in this review, which may have led to the exclusion of non-significant results from the review.

5. Conclusion

To our knowledge, this study is the first attempt to systematically summarise existing findings that investigated associations and transfer effects for attention, interpretation, and recall biases in anxiety. Our review provided preliminary evidence supporting the CCBH in anxiety. Although we found some evidence that cognitive biases were associated and could modify each other, the effects were small. Several factors may have led to our pooled estimated effects being underestimated. However even accounting for this, the true strength of relationships between all three types of bias is likely to be relatively weak. Likewise, although modification of one bias seems likely to influence other biases, the effect using current CBM paradigms is likely to be small. It will be important to conduct further work in the field to address these questions more directly, taking account of our recommendations above. Our review serves as a basis for future studies to further understand the underlying mechanisms of biased information processing in anxiety.

Contributors

CL designed the study and coding manual. CL and research assistant Alicia Tse (A Tse) screened the literature. CL contacted the authors of identified articles for missing data and conducted statistical analyses. CL and A Tse assessed the quality of the included articles. CL wrote the draft of the manuscript. JY provided senior supervision of the study throughout, contributing to the formulation of the research questions, study design and execution, interpretation of results and drafting of the manuscript. AT provided advice on the analyses and drafting of the manuscript. TL provided senior supervision of the study throughout, contributing to the study design, execution and drafting of the manuscript. All authors helped critically revise the article and approved the final manuscript.

Availability of data and materials

All data extracted or analysed during this study are included in this article. The data and analytic codes are available from the first author upon request.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.janxdis.2022.102575.

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