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Larsen, J.K.; Hollands, G.J.; Garland, E.L.; Evers, A.W.M.; Wiers, R.W.

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Be more mindful: Targeting addictive responses by integrating mindfulness with cognitive bias modification or cue exposure interventions

Junilla K. Larsen[a,*], Gareth J. Hollands[b], Eric L. Garland[c], Andrea W.M. Evers[d], Reinout W. Wiers[e]

[a] Behavioural Science Institute, Radboud University, PO Box 9104, 6500 HE Nijmegen, the Netherlands
[b] EPPI Centre, UCL Social Research Institute, University College London, UK
[c] Center on Mindfulness and Integrative Health Intervention Development, College of Social Work, University of Utah, Salt Lake City, USA
[d] Health, Medical and Neuropsychology Unit, Leiden University, NL, and Medical Delta, Leiden University, TU Delft and Erasmus University, UK
[e] Addiction Development and Psychopathology (ADAPT)-lab, Department of Psychology, University of Amsterdam and Centre for Urban Mental Health, University of Amsterdam, the Netherlands

A R T I C L E I N F O

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A B S T R A C T

This review provides an overview of the most prominent neurocognitive effects of cognitive bias modification (CBM), cue-exposure therapy and mindfulness interventions for targeting addictive responses. It highlights the key insights that have stemmed from cognitive neuroscience and brain imaging research and combines these with insights from behavioural science in building a conceptual model integrating mindfulness with response-focused CBM or cue-exposure interventions. This furthers our understanding of whether and how mindfulness strategies may i) facilitate or add to the induced response-focused effects decreasing cue-induced craving, and ii) further weaken the link between craving and addictive responses. Specifically, awareness/monitoring may facilitate, and decentering may add to, response-focused effects. Combined awareness acceptance strategies may also diminish the craving-addiction link. The conceptual model presented in this review provides a specific theoretical framework to deepen our understanding of how mindfulness strategies and CBM or cue-exposure interventions can be combined to greatest effect. This is important in both suggesting a roadmap for future research, and for the further development of clinical interventions.

1. Introduction

Addiction is a prevalent and serious health problem, resulting into various detrimental effects for both physical and mental health (Geller et al., 2017; Hanna et al., 2001), with tremendous costs for not only the individual, but also society (Effertz and Mann, 2013; Sussman et al., 2011). Addictive behaviours are not limited to substance dependence, but also include gambling, and, more contentiously, other behaviours like gaming, internet use and addictive-like eating (Gearhardt and Hebebrand, 2021; LaFata, 2022; Sussman et al., 2011; Webb et al., 2010; Yau and Potenza, 2015). Relapse rates following behavioural and/or pharmacological addiction treatment are high, particularly for those with co-morbid mental health problems (Bradizza et al., 2006; Walitzer and Dearing, 2006). Given that relapse in addictive behaviours has been strongly linked to impulsivity characteristics, particularly strong approach behaviours and a reduced ability to inhibit behaviours (Gullo et al., 2014; Kotov et al., 2010; Pepe et al., 2023; Wiers et al., 2013), researchers have sought to develop intervention techniques that aim to downregulate automatic processes with the aim to prevent relapse. We have recently defined such techniques aimed at individuals with more impulsive characteristics as 'response-focused' strategies (Larsen and Hollands, 2022), as they target cue-induced craving (Rosenthal et al., 2022) and aim to downregulate automatic unwanted (i.e., impulsive) responses during intervention through response modulation and directly changing automatic associations, attentional biases and action tendencies (Larsen and Hollands, 2022). Response-focused techniques for treating addictive behaviours include, but are not limited to, Cognitive Bias Modification (CBM) training and cue-exposure therapy (Larsen and Hollands, 2022). CBM belongs to a family of computerized tasks directly targeting cognitive biases and perception of cues, including Attentional Bias Modification (AtBM), Approach Bias Modification (ApBM), evaluative conditioning and 'selective inhibition training' (e.g., through a

* Corresponding author.
E-mail address: junilla.larsen@ru.nl (J.K. Larsen).

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Go/No-Go task) (Hollands et al., 2011; Houben et al., 2012; Masterton et al., 2020; Rinck et al., 2018; Wiers, 2018; Wiers et al., 2018; Wiers et al., 2013). Exposure therapy directly changes automatic associations by exposing individuals to cues (i.e., in vivo, imagery or virtual exposure) without being allowed to act on them (Conklin and Tiffany, 2002; Ghiţă et al., 2019).

In this conceptual review, we propose that response-focused treatment can benefit from mindfulness-based interventions (MBIs), in which people learn to monitor their present moment experiences with non-reactivity and acceptance, and, as such, increase a state of meta-awareness (Creswell, 2017). We aim to precisely describe and demarcate the specific conditions under which mindfulness techniques may optimally benefit response-focused techniques, namely CBM and cue-exposure training techniques. Previous conceptual papers exist on combining cue-exposure and mindfulness specifically (Treanor, 2011; Vinci et al., 2021). However, there is an absence of a model that explains which mindfulness strategies may add to, or interact with, response-focused techniques in targeting cue-induced craving and/or subsequent addictive responses - a gap we aim to address. Notably, craving is considered to be a prominent mechanism in addictive behaviours (Bernard et al., 2021; Cavicchioli et al., 2020; Sun and Kober, 2020; Vafaie and Kober, 2022). Many theories recognize the importance of learning stimulus-response associations with cues acquiring 'incentive salience', i.e. motivational significance through conditioning to the reinforcing properties of a drug, and the transition from goal-directed to learnt 'compulsive' behaviours (Boswell and Kober, 2016; Hogarth et al., 2013; Lüscher et al., 2020; Perales et al., 2020; Robinson and Berridge, 1993). However, it should be noted that addiction and stimulus-response learning are not purely habitual, but are driven by goal-directed 'drug choice' and inferential learning (Hogarth, 2020; Hogarth et al., 2019; Van Dessel et al., 2018). We use these insights in contexualizing our conceptual model. Such a model is important as it could stimulate theoretically-based future interventions with greater potential for improving health outcomes than those lacking a theoretical foundation (Glanz and Bishop, 2010).

1.1. Article outline

In contextualizing the model, we first outline mechanisms of response-focused and mindfulness strategies separately and discuss limitations of studies combining these strategies. In doing so, we will draw principally on examples from the substance use (e.g., smoking, alcohol, opiates, cannabis, and amphetamines) and addictive-like eating literatures, as illustrative examples of a wider set of addictive-like domains. Despite controversies surrounding addictive-like eating (Gearhardt and Schulte, 2021; Iceta et al., 2021), we specifically include examples regarding binge eating, food-cue reactivity (e.g., attentional bias) and cue-induced unhealthy eating here, given (i) the many prominent examples in the literature and (ii) our conceptual model's focus on cue-induced craving, and the parallels of food-cue reactivity, cue-induced unhealthy eating and binge eating with drug cue reactivity and addiction (Bodell and Racine, 2023; Boswell and Kober, 2016; Gearhardt and Schulte, 2021; Levallius et al., 2022). We also pay specific attention to the underlying neural substrates of response-focused and mindfulness strategies, based on insights from electroencephalogram (EEG) and task-based as well as resting state magnetic resonance imaging (i.e., fMRI and MRI respectively), as this may enhance our understanding regarding mechanisms underlying specific strategies. Moreover, we extend our discussion using important insights from mental health research where this adds to our understanding of mechanisms that may explain addictive outcomes.

It is important to note that this paper does not provide a systematic review of the literature. Instead, we integrate diverse research fields and provide a conceptual review based on a narrative synthesis of the literature. Where possible, we synthesized findings from systematic reviews and meta-analyses across a wide range of different literature fields. Nevertheless, we applied a substantially systematic search strategy for exploring the neural literature. Specifically, we selected EEG and (f)MRI studies according to the following criteria: (i) randomized controlled trials with pre-post neural measurements that compared response-focused or mindfulness treatments/training manipulations with a control condition on addiction-related neural outcomes, or (ii) within-subject designs where the same participant's brain function was measured and compared during response-focused or mindfulness versus control manipulations and related to addiction-related neural outcomes. An initial literature search performed in Google Scholar was carried out in March 2023, consisting of a combination of search words related to response-focused or mindfulness strategies (e.g., cognitive bias modification, approach-avoidance training, Go/No-Go, cue-exposure therapy, mindfulness), neural measures (e.g., neural, fMRI, EEG), addictive outcomes (e.g., addiction, alcohol, smoking, eating) and review studies (e.g., narrative review, systematic review, meta-analysis). The reference lists of included review studies were hand-searched to identify additional eligible articles. Finally, using Google Scholar, we checked cited references of included studies to identify more recent studies, with a last check performed in August 2023. Searches were limited to articles in the English language that were published after 2000. After discussing the mechanisms of response-focused and mindfulness strategies, we present a new conceptual model that explains whether and how mindfulness strategies may i) facilitate or add to the induced response-focused effects decreasing cue-induced craving and ii) further weaken the link between craving and addictive responses. We end our conceptual review by providing recommendations for future research.

2. Narrative synthesis of response-focused and mindfulness mechanisms

2.1. Response-focused strategies

The different types of response-focused strategies have focused on different downregulation mechanisms. A first downregulation mechanism of CBM training tasks includes the targeting of cognitive biases, specifically attentional bias and approach bias. Experts have provided consensus on the relevance of targeting such cue-related cognitive biases in addiction treatment and substance use disorders specifically, and CBM training tasks provide an intervention paradigm to do so (Verdejo-Garcia et al., 2023). Drug-related cues acquire the ability to influence behaviour in part because they acquire incentive motivating properties through stimulus-response learning, and this learning can be 'unlearnt' through newly learnt patterns that may reduce cognitive biases (Flagel et al., 2009). CBM techniques can decrease such biases, but their effects often do not generalize to addictive outcomes (Boffo et al., 2019; Cristea et al., 2016; Yang et al., 2019). With regard to alcohol, reviews indicate that CBM effects on cognitive biases most often do not translate into effects on addictive behaviors in non-clinical populations, but do translate into effects on addictive outcomes in clinical populations treated for alcohol use disorders, with the strongest evidence for ApBM tasks (Wiers et al., 2018; Wiers et al., 2023). With regard to addictive-like eating, two recent meta-analyses suggest that although CBM training changed attention bias towards food cues, effects generalized to reductions in unhealthy eating behaviour for specific CBM trainings, with most consistent effects for Go/No-Go and the least effects for ApBM tasks (Aulbach et al., 2019; Yang et al., 2019). For smoking cessation, CBM results have been less consistent (Heitmann et al., 2018; Kopetz et al., 2017; Machulska et al., 2022; Robinson et al., 2022), and new varieties of training are being considered and developed, including trainings focusing on personalized behavioural (rewarding) alternatives to smoking (Bos et al., 2019; Cheval et al., 2021; Kopetz et al., 2017; Wen et al., 2021; Wiers et al., 2020). For opiates, cannabis, and amphetamines, CBM studies have recently begun to test effectiveness, with similarly mixed, albeit preliminary, findings on cognitive biases, cue-induced craving and amount of use (Ghaffari et al., 2021; Heitmann et al., 2018; Jacobus et al., 2018; MacLean, 2023; Manning et al., 2019; Mayer et al., 2020; Sherman et al., 2018; Zhang et al., 2018).

Besides the targeting of cognitive attentional or approach biases, a second downregulation mechanism (i.e., cue devaluation) includes the targeting of an evaluative bias (Wiers et al., 2013). According to the Behavioural Stimulus Interaction (BSI) theory, appetitive stimuli trigger strong approach reactions, and continuous withholding of these responses to appetitive cues may produce conflicts by continuous oscillation between approach and inhibition of this response. As such, attractive cues are devaluated to resolve this conflict (Veling et al., 2008; Veling et al., 2017). A recent value-updating account additionally suggests that devaluation occurs by action and inaction *decisions* rather than motor inhibition and bottom-up stimulus-response learning (Veling et al., 2022). Cue devaluation mechanisms have mostly been examined using a Go/No-Go training task. Several meta-analytic studies in the field of addictive-like eating, and some studies of alcohol and smoking, have shown evidence for lower explicit, rather than implicit, evaluations of trained No-Go compared to Go and/or untrained pictures, interpreted as evidence for devaluations (Adams et al., 2021; Chen et al., 2018; Chen et al., 2016; Houben et al., 2012; Keeler et al., 2022; Najberg et al., 2021; Quandt et al., 2019; Scholten et al., 2019; Veling et al., 2021; Yang et al., 2022). However, two recent studies, including one well-powered study (Schenkel et al., 2023), suggest that Go/No-Go training did not change explicit alcohol-specific cue-devaluation (Schenkel et al., 2023; Stein et al., 2023). Besides Go/No-Go training tasks, other response-focused strategies in the addiction field may work by modifying explicit cue evaluations. This has been little examined, but there are more recent exceptions (Di Lemma and Field, 2017; Kakoschke et al., 2017; Machulska et al., 2022; Veling et al., 2021). Additional adequately powered and rigorous studies comparing different CBM tasks within the same study are needed to examine whether or not specific CBM techniques may influence cue-devaluation differently, and whether these effects may also differ based on the addiction or target group under consideration.

A final, more 'top-down' cognitive downregulation mechanism includes 'expectancy violation', explaining cue-exposure effects on binge eating (Magson et al., 2021). Specifically, cue-exposure directly interferes with automatically activated processes through exposing individuals to cues without being allowed to act on them, maximizing the mismatch between the expected (e.g., 'If I see cookies, I can't control my eating') and actual cue exposure outcome (i.e., the amount of 'expectancy violation') (Schyns, Roefs et al., 2020; Schyns, van den Akker et al., 2020). A systematic review suggests consistent 'expectancy violation' mechanisms across five studies, stimulating reductions in the frequency of binge eating (Magson et al., 2021). Moreover, in the field of mental health – where exposure therapy for anxiety disorders is a gold standard treatment (Chowdhury and Khandoker, 2023; Weisman and Rodebaugh, 2018) – violation of dysfunctional expectancies is a key mechanism determining exposure therapy outcomes (Craske et al., 2014; Foa and McLean, 2016; Pittig et al., 2016; Rief et al., 2022; Schemer et al., 2020). Of note, in contrast to these promising findings in the field of binge eating and mental health, effects of cue-exposure therapy prove less consistent for substance-related addictions (Kiyak et al., 2022; Langener et al., 2021; Lee et al., 2009; Malbos et al., 2022; Marissen et al., 2007; Mellentin et al., 2017; Pericot-Valverde et al., 2019; Trahan et al., 2019; Wang et al., 2019). We speculate that this may be because specific substance-use related withdrawal effects may elicit intrusive thoughts and craving experiences that interfere with the generalization of cue-exposure effects to daily life. Of note, the efficacy of cue exposure therapy on alcohol use disorders is greater if combined with specific coping skills training (Kiyak et al., 2022). Moreover, studies that added aversive counterconditioning to exposure therapy (e.g., through explicitly pairing drug-related cues with adverse consequences or nausea during virtual reality that was accidentally associated with tobacco cues) also appear more promising than standard cue exposure therapy studies regarding reductions in craving and use (Lee et al., 2009; Malbos et al., 2022; Wang et al., 2019), although rigorous studies comparing different cue-exposure procedures within the same study are needed. Overall, the idea that challenging beliefs regarding the ability to withstand substance use craving is important for cue exposure effectiveness has been widely acknowledged, but researchers have not yet systematically studied its mechanisms in the field of addiction (Byrne et al., 2019).

To conclude, although the literature is not limited to the three downregulation mechanisms discussed above – namely a reduction in cognitive biases, an increased cue-devaluation, and 'expectancy violation' – they act as prominent examples investigated in different addictive-like domains using specific response-focused strategies. Despite differences, all type of response-focused strategies share an overarching common element, namely the focus on the downregulation of cue-induced craving, as mentioned (Larsen and Hollands, 2022; Rosenthal et al., 2022). As such, we can speculate that there are also similarities regarding underlying downregulation mechanisms. This has also been noted by others recently regarding CBM tasks specifically, necessitating further direct comparisons between tasks to elucidate similarities in underlying mechanisms (Houben and Aulbach, 2023).

2.1.1. *Neural effects of response-focused techniques*

Neuroimaging studies may further improve our understanding of why specific response-focused trainings are effective. Until 2016, addiction studies on the neural effects of CBM were limited to two alcohol-specific ApBM (f)MRI studies (Wiers et al., 2015; Wiers et al., 2015), as identified by different reviews (Cabrera et al., 2016; Verdejo-Garcia, 2016; Wiers and Wiers, 2017). In a first alcohol-specific fMRI study, ApBM, compared to sham control training, decreased amygdala activity while passively viewing alcohol cues, which correlated with decreased craving in the treatment training treatment group only (Wiers, Stelzel et al., 2015). In a second follow-up study, a subset of patients also performed the ApBM in MRI (Wiers, 2015a). Results showed a reduction in medial prefrontal cortex (mPFC) activation in the CBM group only, which was associated with reductions in automatic alcohol approach bias and self-reported bias, but not craving (Wiers et al., 2015b). Although these studies found no effect of CBM on the behavioural approach bias, they suggest that alcohol ApBM training may impact common brain structures involved in cue-reactivity, motivational salience of cues, approach bias and, specifically 'wanting' rather than 'liking' (Hill-Bowen et al., 2021; Warlow and Berridge, 2021; Wiers and Wiers, 2017; Zeng et al., 2021). In line with this, a food-specific ApBM also found that the training group had weaker unhealthy food approach tendencies, paralleled by a lower activation in the right angular gyrus (Mehl et al., 2019), indicating changes in attentional processes (Seghier, 2023), while little evidence was found for altered reward valuation of food (Mehl et al., 2019).

By contrast, and as noted by others (Veling et al., 2022), more recent fMRI Go/No-Go training studies in the field of addictive-like eating found evidence for changes in the reinforcing value of appetitive stimuli and a hedonic 'liking' cue-devaluation mechanism (Stice et al., 2017; Yang et al., 2023), although null results have also been observed, explained by the use of heterogeneous food images (Stice et al., 2022). Specifically, Go/No-Go training, alone or in combination with other CBM tasks, reduced activity in reward-related brain areas in response to high-caloric food images, while no such effects were found in the control sham (non-food) training among individuals with overweight or obesity (Stice et al., 2017; Yang et al., 2023). It is worth noting that one fMRI study examined total effects of five different CBM training tasks, including Go/No-Go training and other inhibitory control and attention training tasks, and could thus not separate the unique contributions of training tasks (Stice et al., 2017), while the other study examined neural mechanisms of Go/No-Go training specifically (Yang et al., 2023). Importantly, reductions in responsivity in the mid-insula were positively associated with food-cue devaluations in both studies (Stice et al., 2017; Yang et al., 2023). This 'mechanistic' role of the insula is in line with findings of reviews and a meta-analysis of fMRI studies showing that the insula is activated in reward anticipation and translating subjective experiences of craving and urge to use (Droutman et al., 2015; Liu et al., 2011; Naqvi and Bechara, 2009; Naqvi et al., 2007; Noël et al., 2013). However, a recent meta-analysis shows that insula activity was observed after natural reward-related stimuli (sexual or food-related) rather than drug-specific stimuli (nicotine, alcohol, cannabis, cocaine and heroin) (Hill-Bowen et al., 2021). As such, the 'mechanistic' role of the insula underlying cue-devaluation effects might also be non-drug specific rather than drug-specific. Consistent with this idea, some recent studies from behavioural science suggest that Go/No-Go training did not change alcohol-specific cue-devaluation (Schenkel et al., 2023; Stein et al., 2023), as mentioned, but more research across addictions is needed.

EEG or fMRI studies question the mechanism of Go/No-Go training in targeting top-down cue-related inhibitory control (Aulbach et al., 2020; Carbine et al., 2021; Grieder et al., 2022; Veling et al., 2022; Yang et al., 2023). Specifically, a food Go/No-Go training did not affect the amplitude of the N2 ERP component (an indicator of inhibitory control) during the completion of the Go/No-Go task in a within-subject laboratory study (Aulbach et al., 2020). These null results regarding N2 ERP were further supported in a relatively large randomized controlled trial where individuals with overweight or obesity were assigned to complete generic or food-specific Go/No-Go training four times per week for four weeks (Carbine et al., 2021). In addition, one fMRI study specifically tested alcohol-specific Go/No-Go training changes in activation of the right inferior frontal gyrus, characterized as 'a brake', (Aron et al., 2014) and found no evidence for such training changes among patients with alcohol use disorder (Grieder et al., 2022), while another fMRI study even found evidence for decreased, rather than increased, activation in inhibitory control regions to high-calorie food images after a food-specific Go/No-Go training (Yang et al., 2023). It is possible that increased explicit cue-devaluation reduces the need for top-down control (Yang et al., 2023). Interestingly, one EEG study found that, during passively viewing food pictures, theta power at frontal midline electrodes was larger for food stimuli that were previously paired with 'no-go' as compared to 'go' responses (van de Vijver et al., 2018). As higher frontal midline theta activity may be indicative of more brain plasticity and effortless control (Tang et al., 2019), we might speculate that a Go/No-Go training increases effortless control partly through enhanced cue-devaluation. Future work is needed to test this hypothesis.

Overall, these first neural studies provide support for down-regulation mechanisms. Their findings suggest that Go/No-Go non-drug specific tasks may result in cue devaluation, while ApBM tasks may change attentional and/or approach biases rather than 'liking' or cue-devaluation across addictions. However, another fMRI study among cannabis users suggest that ApBM did not modify neural (bias-related) cue-reactivity (Karoly et al., 2019), and, an alcohol-specific EEG study also found no neural or behavioural effects of ApBM training in a hazardous drinking population (den Uyl et al., 2016). As such, neural downregulation mechanisms of CBM trainings might differ based on the addiction or target group under consideration.

Besides these neural CBM studies, a recent review (Agarwal et al., 2021) identified two cue exposure treatment fMRI studies in the field of obesity and alcohol (Becker et al., 2018; Vollstädt-Klein et al., 2011). Below, we will discuss the findings of these studies, in combination with an EEG study (Lee et al., 2009) and two studies employing fMRI that presented first results of single prolonged cue-exposure sessions (Ekhtiari et al., 2021; Frankort et al., 2014). Similar to the first neural effects of CBM trainings concerning alcohol and eating, a study in the treatment of alcoholism found that cue-exposure therapy in addition to care-as-usual led to a relatively larger decrease of fMRI cue reactivity in the bilateral anterior cingulate gyrus, the left precentral gyrus, the left insula, the bilateral inferior parietal lobule, the left superior frontal gyrus, the right middle frontal gyrus, and the left ventral and the left dorsal striatum than sole care-as-usual (Vollstädt-Klein et al., 2011). These relative decreases were the result of reduced brain activation in the anterior cingulate and frontal regions (middle frontal gyrus and superior frontal gyrus) after cue exposure therapy, but increases in cue-induced activation in the insula, the precentral gyrus, and several frontal regions in the care-as-usual group. Meta-analytic evidence shows that alcohol cues generally evoke greater cue-reactivity than neutral cues in the anterior cingulate cortex, the middle cingulate, and the right medial prefrontal cortex in alcohol use disorder patients compared to healthy controls (Zeng et al., 2021). As such, cue-exposure therapy seems to reduce neural cue-reactivity to alcohol cues.

Decreases in 'cue-reactive' brain areas are also observed in some other addiction-specific prolonged single session cue-exposure studies (Ekhtiari et al., 2021; Frankort et al., 2014). Specifically, a recent single within-subject cue-exposure session among individuals with methamphetamine and opioid use disorder who were abstinent during early treatment showed ventral-medium-prefrontal-cortex, right amygdala and bilateral ventral striatum habituation (i.e., decreased activation) to repeated drug cue, but not neutral cue, presentation, also a few days later (Ekhtiari et al., 2021). Although these habituation effects were replicated in different samples, participants received treatment in between test and retest time points, which could have contributed to the habituation effects (Ekhtiari et al., 2021). Moreover, another fMRI study found that, compared to exposure to a control stimulus, a single prolonged chocolate cue-exposure session resulted in lower brain activation in areas that have been mostly implicated in food reward, including the left and right caudate, left striate cortex, and bilateral extrastriate cortex, and on the border of the right parahippocampal gyrus with the lingual and posterior cingulate gyrus, while in the beginning of the exposure session the pattern was reversed (Frankort et al., 2014). Of note, these neural studies found no direct significant effects of (prolonged) cue-exposure on reductions in self-reported craving (Ekhtiari et al., 2021; Frankort et al., 2014; Vollstädt-Klein et al., 2011). However, one study observed that craving started to decrease, suggesting that the decline in brain reward activation in the cue-exposure group might be a precursor of a decrease in follow-up craving (Frankort et al., 2014). Future research is needed to examine future (follow-up) craving effects, as well as different cue-reactive down-regulation mechanisms (e.g., cue-devaluation).

In an EEG study, cognitive therapy combined with cue exposure therapy and aversive counterconditioning resulted in increased alpha waves in prefrontal cortex areas (i.e., Fp2-A2 and F8-A2) in patients with alcohol dependence, while cognitive therapy alone did not result in such changes (Lee et al., 2009). Although the exact mechanistic role of increases in alpha power remains unclear, recent reviews suggest that it reflects different facets of top-down cognitive control and possible decreases in task demands and cognitive workload (Chikhi et al., 2022; Clayton et al., 2018; Sadaghiani and Kleinschmidt, 2016). A final fMRI study among alcohol use disorder patients provides some further support for the idea that cue-exposure therapy may also impact the way some patients learn to regulate their alcohol consumption (Becker et al., 2018). This study investigated non-drug reward sensitivity and found that higher baseline reward sensitivity in the ventral striatum during the anticipation of monetary (compared to verbal feedback) reward was linked to increased activation in the superior frontal gyrus and the anterior cingulate cortex after cue-exposure treatment for alcohol use disorder (Becker et al., 2018). As this increased activation was positively associated with self-efficacy to abstain from alcohol, non-drug reward enhanced striatal sensitivity may determine effects of cue-exposure treatment on prefrontal cortex processes related to self-regulation (Becker et al., 2018). Nevertheless, meta-analytic data of individuals with substance addictions, compared to healthy controls, showed decreased, rather than increased, striatal activation during non-drug momentary reward anticipation (Luijten et al., 2017). However, a previous study (Becker et al., 2017), using the same task as used in the cue-exposure treatment study (Becker et al., 2018), found increased activation of the ventral striatum during anticipation of monetary gain in individuals with alcohol use disorder compared to healthy controls

(Becker et al., 2017). These findings are most likely explained by differences in task design (Becker et al., 2017). Specifically, the reward task used in the cue-exposure study may have elicited a more precise prediction of the rewarded task and, as such, may have elicited more similarities with the reward outcome phase, where individuals with substance use addiction similarly showed increased activation in the ventral striatum (Luijten et al., 2017). Although these findings may suggest that individuals with enhanced striatal sensitivity to non-drug rewards may profit most from cue-exposure therapy, more research examining differential effects of non-drug and drug-specific cues is needed.

2.2. Mindfulness-based intervention strategies

As mentioned, mindfulness-based interventions (MBIs) aim to increase a state of meta-awareness in which people learn to monitor their present moment experiences with non-reactivity and acceptance (Creswell, 2017). There are many forms of mindfulness-based interventions with different durations, ranging from 3-month retreats to very brief mindfulness interventions with a duration of 30 min or less on any occasion and ranging 4–8 weeks (Creswell et al., 2019; Hogarth et al., 2019). Mindfulness practices are integrated with other practices such as targeting stress/coping reactions in Mindfulness-based Stress Reduction (MBSR) or mindfulness-based cognitive therapy (MBCT) integrating mindfulness practice with cognitive behavioural therapy (Kabat-Zinn, 2003; Sipe and Eisendrath, 2012). These mindfulness-based interventions (MBIs) have also been used for many addictive behaviours, including MBIs for binge eating, Mindfulness-based Relapse Prevention (MBRP) and Mindfulness Training (MT) for Smokers specifically (MTS), and Mindfulness-Oriented Recovery Enhancement (MORE) for addiction (Garland, 2016; Garland et al., 2019; Godfrey et al., 2015; Oikonomou et al., 2017; Parisi et al., 2022). Moreover, "third wave cognitive and behavioural" interventions that use mindfulness as a smaller component within a larger set of techniques (Schuman-Olivier et al., 2020; Tapper, 2022) have also been used in similar addiction contexts (Sancho et al., 2018).

Although large and rigorous randomized controlled trials of specific mindfulness therapies (e.g., MORE, MBRP) as a treatment for addiction have been conducted (Bowen et al., 2014; Garland et al., 2022), reviews have often investigated a range of MBIs and "third wave" interventions, impeding conclusions regarding the specific effects of mindfulness on for instance binge eating disorder (Mercado et al., 2021). Nevertheless, a growing body of review and meta-analytic evidence suggests that MBIs are effective in reducing addictive behaviours, including smoking, alcohol use and addictive-like eating, although more highly powered mechanistic studies with long-term follow-ups are needed to further understand these effects (Goldberg et al., 2021; Korecki et al., 2020; Li et al., 2017; Mercado et al., 2021; Parisi et al., 2022; Roche et al., 2019; Schuman-Olivier et al., 2020; Tapper, 2022). Although the working mechanisms of MBIs for addiction are understudied, as mentioned, Rosenthal and colleagues have recently distinguished three principal ways in which MBIs may impact the course of addictive disorders, including increased top-down cognitive control and decreased cue-reactivity and stress perception (Rosenthal et al., 2021).

2.2.1. Neural effects of mindfulness-based interventions

Rosenthal and colleagues have recently discussed (neuroimaging) studies that support these three principal ways in which MBIs may impact the course of addictive disorders (Rosenthal et al., 2021). We now briefly summarise the findings of Rosenthal and colleagues (see Rosenthal et al., 2021, 2022 for a further discussion on the specific studies) and add further insights from other reviews and recent studies. Regarding decreases in cue-reactivity, Rosenthal and colleagues (Rosenthal et al., 2022; Rosenthal et al., 2021) discuss several studies showing that MBIs reduced (neuronal) cue-induced craving (Froeliger et al., 2017; Garland et al., 2023; Garland et al., 2014, 2015; Hanley and Garland, 2020; Janes et al., 2019; Westbrook et al., 2013), addiction-related attentional bias (Garland et al., 2017; Garland et al., 2010; Garland et al., in press) and (neuronal) stress reactivity attenuating addictive responses (Davis et al., 2018; Garland et al., 2017; Garland, Hanley et al., 2019; Kober et al., 2017). Regarding top-down cognitive control, they cite several studies showing that MBIs lead to increases in reflective decision-making, decreased efforts to inhibit responses or increases in brain prefrontal cognitive control networks (Andreu et al., 2018; Garland et al., 2019; Garland and Howard, 2018; Rosenthal et al., 2021; Tang et al., 2013; Valls-Serrano et al., 2016).

In contrast, there are also studies showing that mindfully accepting craving (smoking sample) and pain or negative emotion (normative sample) do not recruit prefrontal regions (Kober et al., 2019; Westbrook et al., 2013). A recent systematic review of fMRI studies in people with substance dependence, principally concerning tobacco, supports the idea that MBIs are not only associated with changes in the function of brain pathways implicated in reward processing (e.g., anterior cingulate cortex and the striatum), but also in additional higher order cognitive regions (precuneus, inferior frontal gyrus) (Lorenzetti et al., 2023). However, this fMRI evidence is still limited, as studies had relatively small samples sizes, and some also lacked pre-post fMRI measurement, control groups or randomized allocation to groups (Lorenzetti et al., 2023). In the field of addictive-like eating, fMRI evidence is even more limited. We found only one recent fMRI study that fulfilled our search criteria (Janssen et al., 2023). This study found reduced reward midbrain food reward anticipation after an intensive mindful eating intervention compared to an active control intervention, but these effects were not anticipated, and were not significant in the whole-brain corrected analysis (Janssen et al., 2023). Of note, recent meta-analyses of behavioural data generally support the effects of MBIs on increasing self-regulation and executive control (Básedas et al., 2020; Leyland et al., 2019), although further investigation in the field of addiction is needed (Brandtner et al., 2022). Moreover, a recent meta-analysis of resting-state fMRI frontoparietal functional connectivity of brain networks suggests that functional connectivity is related to mindfulness (i.e., operationalized as both a trait and MBIs) (Sezer et al., 2023). Specifically, the cingulate cortex played a major role in this connectivity across multiple (prefrontal) modalities, with increased connectivity of different parts of the cingulate cortex with dorsolateral prefrontal cortex ('attention control') and dorsomedial prefrontal cortex ('emotion regulation') (Sezer et al., 2023). Furthermore, systematic reviews and/or meta-analyses of EEG studies have shown that mindfulness meditation mostly increases amplitude in the frontal midline alpha and/or theta bandwidths (Lee et al., 2018; Lomas et al., 2015). These increases are associated with decreases in cognitive workload, but increases in self-regulation, working memory functioning, conflict modulations, sustained attention and, specifically for frontal midline theta bandwidths, probably also with more effortless control, as mentioned (Chikhi et al., 2022; Hsieh and Ranganath, 2014; Jo et al., 2017; Mitchell et al., 2008; Tang et al., 2019).

As such, it is not surprising that recent randomized controlled EEG studies among opioid users found that effects of MBIs (i.e., MORE) on decreasing opioid use and misuse were mediated by increased frontal midline theta activity (Garland et al., 2022; Hudak et al., 2021). In a recent study, which is to our knowledge the largest neuroscientific study of mindfulness as a treatment for addiction, MORE, compared to a supportive psychotherapy control condition, produced significantly greater increases in frontal midline theta spectral power and coherence during a laboratory-based mindfulness meditation session. These increases in both power and coherence mediated the effect of MORE on reduced opioid use at 9 months follow-up (Garland, et al., 2022). Similar mediation by changes in frontal theta power was found in a previous MORE pilot study that had a modest sample size (Hudak et al., 2021). MORE integrates traditional mindfulness meditation techniques with reappraisal and savoring strategies to strengthen top-down cognitive control functions as a means of restructuring bottom-up reward learning from valuation of drug-related rewards (i.e., decrease drug cue-reactivity) back to valuation of natural rewards (i.e., increase natural reward responsiveness) (Garland, 2016). Indeed, prior autonomic, EEG, and fMRI studies have also shown MORE to decrease reactivity to drug cues while increasing responsiveness to natural rewards (Froeliger et al., 2017; Garland et al., 2019a; Garland et al., 2014; Garland, Howard et al., 2017). However, MORE and many other MBIs are multicomponent interventions, and the studies discussed so far did not compare effects between different mindfulness strategies.

2.2.2. Mindfulness dismantling studies

As MBIs are quite heterogeneous, consisting of different mindfulness strategies, it is not surprising that there are a growing number of recent high-quality behavioural mindfulness ‘dismantling’ intervention studies in the field of mental health, where mindfulness has been studied more extensively during the past decades. These studies are discussed below as they provide further insights into specific MBI mechanisms (e.g., stress reactivity) relevant for response-focused addictive outcomes. To date, these mindfulness intervention studies often compare awareness or monitoring, this concerning attending to present moment experiences, with acceptance skills training to stimulate the acceptance of thoughts and emotions without judging them. This comparison follows from the monitor and acceptance theory, suggesting that only attention/awareness combined with an accepting stance diminishes negative affect reactivity (Lindsay and Creswell, 2017). Such dismantling studies support this component of monitor and acceptance theory, suggesting that awareness (i.e., monitoring) is particularly effective when combined with acceptance skills training, for regulating affect, decreasing emotional reactivity, stress ratings and objective stress measures, and boosting positive emotions (Chin et al., 2019; Lindsay et al., 2018; Lindsay et al., 2018; Stein and Witkiewitz, 2020). As concluded by a recent systematic review, acceptance coupled with awareness holds promise as an important active ‘stress-reducing’ ingredient of mindfulness-based interventions (Stein and Witkiewitz, 2020). Although these dismantling studies from mental health research may yield promise for the field of addiction, where the ability to ‘sit with discomfort’ may have high applicability to craving and negative affect or distress, acceptance strategies alone do not appear to be promising in targeting addictive-like eating (Tapper, 2022). Future research is needed to examine the neural substrates of the effects of acceptance coupled with awareness.

Moreover, monitor and acceptance theory also suggests that the training of attention monitoring skills mainly underlies effects on attention-related mechanisms (Lindsay and Creswell, 2017). Although this has been examined less often, a recent high-quality dismantling study has shown evidence for this idea (Chin et al., 2021). Specifically, relative to a no treatment control condition, both monitor and accept training during a standard 8-week MBSR intervention and a well-matched modified 8-week MBSR-adapted intervention that focused on monitoring skills only resulted in equivalent improvements in momentary and trait attentional control (Chin et al., 2021). In addition, recent meta-analytic results suggest that attentional improvements can be achieved by teaching focused attention meditation, to encourage shifting attention towards a specific attentional target, such as breathing, and away from thoughts, and/or teaching open monitoring meditation, to direct attention towards any thought or emotion in an open-minded way (Sumantry and Stewart, 2021). Although both types of meditation practices might thus be possible ways to target awareness/monitoring, some other recent dismantling studies comparing focused attention and open monitoring meditation trainings suggest that focused attention practices are more important for improving emotion regulatory skills and mental health compared to open monitoring practices (Brown et al., 2022; Lohani et al., 2020). Of note, EEG oscillation contrasts also suggest distinct differences in neural activity among these different meditation practices (Lee et al., 2018) and specific longitudinal data in non-meditators suggests that the changes in neural activity caused by focused attention meditation practices modulated attention (Yoshida et al., 2020). Further neurocognitive research is needed to deepen understanding of how these different meditation training practices can be fueled by specific awareness and/or acceptance skills training, included in both meditation instructions and other didactic mindful content.

Besides these present moment awareness and acceptance strategies more intensively investigated in the field of mental health, another key feature strategy of mindfulness is decentering (Tapper, 2022). Decentering has been defined as the metacognitive process of creating distance and distinguishing oneself as separate from the experiences, such as thoughts, emotions or physical sensations (Bernstein et al., 2015). The specific strategy of mindful decentering has mainly been examined in the field of addiction. To date, a recent review concludes that decentering strategies may be helpful for craving management (Tapper, 2022). Specifically, there is a growing body of psychological experiments suggesting that decentering is a promising mindful strategy to deal directly with food cravings (Keesman et al., 2017, 2020; Papies et al., 2016; Tapper and Turner, 2018; Wilson et al., 2021). These experiments included a food-exposure craving induction, after which participants were instructed to focus on the high-calorie palatable food while they received general (e.g., imagine placing any thoughts or feelings into a leaf and watch it float down the stream) or food-specific (e.g., observe reactions to the high calorie foods as passing mental events) decentering instructions. Theoretically, decentering strategies may reduce craving by preventing craving-related thoughts, specifically through reducing the believability of intrusive craving-related thoughts (Papies et al., 2020) and increasing the accessibility of other thoughts and goals that are important to the individual (Tapper and Ahmed, 2018). However, although these psychological experiments can be informative, they also carry the risks of oversimplifying mindfulness interventions to specific techniques in a toolbox (Powell, 2014; Schuman-Olivier et al., 2020). Notably, decentering has also been regarded as a key mechanism explaining mental health improvements stimulated through more intensive MBIs that focus on combined present moment awareness and acceptance (meditation) training (Bennett et al., 2021; Hanley et al., 2021; Hanley et al., 2020; Levi et al., 2021; Moore et al., 2022). As such, we suggest that a clear distinction should be made between targeting decentering as a separate mindful *strategy* and changing decentering *mechanisms* in MBIs. Combined present moment awareness and acceptance training, as is cultivated in MBIs like MBSR and MORE, aims to provide longer-term insights that one’s thoughts and experiences are transient and fleeting mental events that are separate from oneself and not necessarily a true reflection of reality. This contributes to a state of decentering in which thoughts and experiences can be observed from a real metacognitive perspective. In contrast, a simple decentering strategy in a cue-food exposure craving induction will probably not lead to these insights. Nevertheless, the mindful eating literature suggests that decentering strategies may be helpful for craving management even without further mindfulness training (Tapper, 2022).

2.3. Combined response-focused and mindfulness strategies

There are only a few studies that have combined mindfulness-based with response-focused intervention strategies. In the field of anxiety and chronic pain disorders, combined cue-exposure and mindfulness-based (awareness) interventions have been developed (Hedman-Lagerlöf et al., 2019; Hesser et al., 2018). However, little is known about combined effects, as the designs of these intervention studies did not allow the investigation of interaction effects (Hedman-Lagerlöf et al., 2019; Hesser et al., 2018). In the field of addiction, however, there is some initial evidence from psychological experiments for combined effects of response-focused (i.e., cue-exposure or CBM techniques) and mindfulness meditation and awareness strategies with regard to reductions in addictive-like eating and smoking (Andreu et al., 2018; Bowen and Marlatt, 2009; Fisher et al., 2016; Forman et al., 2016). This evidence should be regarded as highly preliminary, given the generally small sample sizes, limited follow-up measures, or absence of control condition(s). Future high-quality research is needed to increase insight into the combined effects of response-focused and mindfulness techniques on addictive outcomes. Specifically, adequately powered and rigorous studies comparing single and combined effects are needed across different addictions. Examples of what these experiments and interventions may look like are presented in part 4.1 (directions for future research). This research can benefit from insights regarding specific underlying (combined) working mechanisms.

3. Conceptual model (Fig. 1)

In Fig. 1 we present a model that differentiates mindfulness strategies according to whether they may i) facilitate or add to the induced response-focused mechanisms decreasing cue-induced craving (paths 1a-1c) and ii) further weaken the link between craving and addictive responses (path 1d). With regard to paths 1a, downregulation mechanisms (e.g., explicit cue devaluation, a reduction in cognitive biases and 'expectancy violation') may be amplified by mindfulness present moment awareness strategies. We suggest that present moment awareness might particularly stimulate downregulation mechanisms, as the training of present moment awareness/open monitoring/focused attention (meditation) skills mainly underlies effects on improvements in attentional mechanisms, as mentioned (Chin et al., 2021; Sumantry and Stewart, 2021). These attentional improvements may particularly benefit response-focused downregulating mechanisms, as the attention/awareness of stimulus-response contingencies has shown to stimulate effects of CBM trainings (Hofmann et al., 2010; Van Dessel et al., 2016), and, specifically, attention paid to stimuli during a Go/No-Go training seems to elicit stronger cue devaluation effects (Quandt et al., 2019). In addition, Go/No-Go trainings within fMRI context may also increase attentional focus, by performing tasks in a scanner without further distracting information, and provide further neural support for this cue-devaluation mechanism, as mentioned (Stice et al., 2017; Yang et al., 2023), although attention was not manipulated in these studies. Moreover, attention during cue-exposure is similarly considered important, as it highlights 'expectancy violation', a crucial mechanism to effective food-cue exposures, as mentioned (Magson et al., 2021). In a combined cue-exposure-mindful awareness intervention in the context of anxiety and chronic pain disorders, exposure effects were importantly generated through reduced avoidance (Hedman-Lagerlöf et al., 2019; Hesser et al., 2018). This might suggest that mindful attention during exposure has played a role in facilitating these exposure mechanisms. However, the designs of these studies did not allow the investigation of specific effects, as mentioned (Hedman-Lagerlöf et al., 2019; Hesser et al., 2018). Future research is needed to examine whether present moment awareness strategies *during* response-focused strategies may be particularly helpful in facilitating downregulating mechanisms through increased attention, in line with an inferential account (Hogarth, 2020; Hogarth et al., 2019; Van Dessel et al., 2018).

Moreover, we suggest that decentering strategies utilized *after* response-focused techniques (paths 1b, Fig. 1) may further prevent later cue-induced craving reactions. This would likely be attributable to added effects due to an increased 'dose'. Theoretically, it might be easier to resist cues in daily life if experienced cue-induced craving is further lowered by decentering techniques that are theorized to reduce craving-related thoughts, as mentioned (Papies et al., 2020; Tapper and Ahmed,

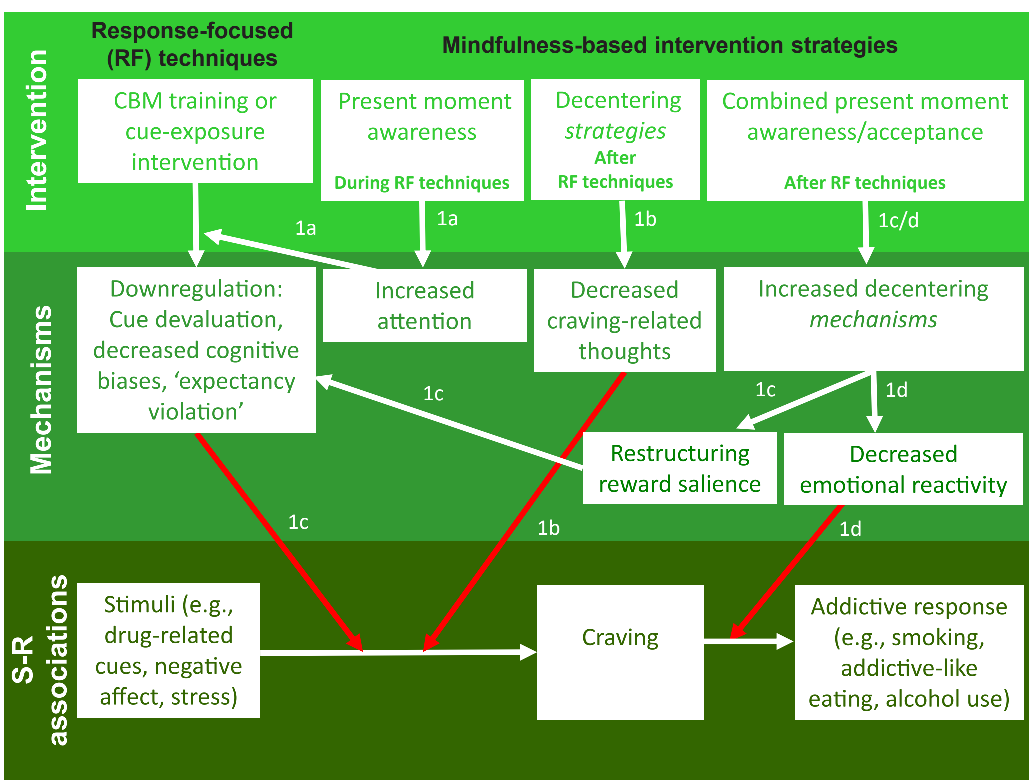

Fig. 1. A conceptual model of how mindfulness strategies may influence response-focused (RF) mechanisms and addictive responses (paths 1a-1d). Note. S-R associations = Stimulus-Response associations. Red arrows represent decreasing effects; White arrows represent increasing effects. CBM = Cognitive Bias Modification. Our model proposes that awareness/monitoring may facilitate (paths 1a), and decentering may add to (paths 1b), the induced response-focused effects decreasing cue-induced craving. Combined awareness acceptance strategies may also add to response-focused effects decreasing cue-induced craving (paths 1c), but may weaken the link between craving and addictive responses as well (paths 1d). Of note, a clear distinction has been made between targeting decentering as a separate mindful *strategy* and changing decentering *mechanisms*.

2018). Nevertheless, we propose that the temporal order in which mindfulness decentering and response-focused strategies are presented is important for its combined effectiveness. Decentering strategies that decrease cue-induced craving *during* response-focused techniques may actually impede the therapeutic potential of response-focused interventions in which people need to engage with the challenge by exerting high attention in order to modulate it. There is no direct empirical evidence yet to support this hypothesis, but given the effects of specific decentering strategies on cue-induced craving (Keesman et al., 2017, 2020; Papies et al., 2016; Tapper, 2022; Tapper and Turner, 2018; Wilson et al., 2021), we identify this as an important future research avenue. Also, the time course of these processes remains largely unknown. Studies are needed to determine how long a patient should be exposed to a drug cue before engaging in decentering strategies.

Finally, we suggest that specifically combined mindful (meditation) awareness and acceptance strategies, often forming the core component of MBIs, may target downregulation mechanisms, such as attentional bias (Garland, Baker et al., 2017; Garland et al., 2010; Garland et al., in press), and subsequent cue-induced craving (Froeliger et al., 2017; Garland et al., 2023; Garland et al., 2014, 2015; Hanley and Garland, 2020; Janes et al., 2019; Westbrook et al., 2013), as mentioned (paths 1c). Moreover, these combined strategies may particularly be important for further generalization of response-focused mechanisms to (longer-term) addictive responses (paths 1d). Longer-term MBIs may facilitate the integration of combined aspects of awareness and acceptance in daily life, stimulating decentering *mechanisms* that may explain mental health outcomes, as mentioned (Bennett et al., 2021; Hanley et al., 2021; Hanley et al., 2020; Levi et al., 2021; Moore et al., 2022). Specifically, combined awareness and acceptance strategies generally reduce emotional reactivity (path 1d), including reduced stress-reactivity, negative affect and increased self-control (Blanck et al., 2018; Im et al., 2021; Stein and Witkiewitz, 2020; Yakobi et al., 2021). Further, as Garland proposes in his *restructuring reward hypothesis*, mindfulness might amplify savoring of non-drug rewards and thereby facilitate cue devaluation and downregulation (paths 1c) by restructuring reward salience mechanisms from valuing drug rewards back to valuing natural rewards (Garland, 2021); in that regard, MORE has been shown to increase neurophysiological responses to natural reward cues while decreasing cue-reactivity toward drug cues, as mentioned (Froeliger et al., 2017; Garland et al., 2019; Garland et al., 2014; Garland, Howard et al., 2017). As such, these combined mindful strategies may prevent important triggers for relapse (Bresin et al., 2018; Heckman et al., 2017).

Some behavioural and neuroimaging studies indeed support the idea that MBIs, consisting of combined awareness and acceptance strategies, may reduce addictive responses and relapse through building resilience to stress and negative affective triggers, as mentioned (Davis et al., 2018; Garland, Bryan et al., 2017; Garland, Hanley et al., 2019; Kober et al., 2017). Moreover, mindfulness leads to enhanced frontal theta oscillations (Lee et al., 2018; Lomas et al., 2015) and the addiction reducing effects of MBIs appear to be mediated by such increases in theta oscillations (Garland et al., 2022; Hudak et al., 2021), possibly decreasing drug cue-reactivity through more effortless self-regulation (Tang et al., 2019). Although response-focused treatments may also enhance theta power at frontal midline electrodes (van de Vijver et al., 2018), most studies provide evidence for reduced cue-reactive activation in attentional and reward-related brain areas after treatment, as mentioned. As such, we only include a path from response-focused treatments to downregulation mechanisms, but not to reduced emotional reactivity. Moreover, although resilience regarding stress reactivity may also attenuate stress-induced craving, such 'stress-craving' effects were not specific to mindfulness interventions (Carroll and Lustyk, 2018) and null results were found as well (Davis et al., 2018). As such, we only include a moderating link from 'decreased emotional reactivity' to the 'craving-addictive response' link (path 1d), while no such moderating path has been added to the 'stimuli-craving' link in Fig. 1. To conclude, our model proposes that mindful awareness/monitoring may facilitate (paths 1a), and decentering may add to (paths 1b), the induced response-focused effects decreasing cue-induced craving. Combined awareness and acceptance strategies may also add to response-focused effects decreasing cue-induced craving (paths 1c), but may weaken the link between craving and addictive responses as well (paths 1d). Our model is necessarily a simplification (e.g., downregulation mechanisms may impact addictive stimuli). Moreover, given the limited empirical studies performed, the pathways in Fig. 1 represent working hypotheses that require corroboration in future research.

4. Discussion

4.1. Directions for future research

We propose some suggestions for future research. First, future experiments are needed that focus on investigating and comparing underlying shorter-term neural mechanisms of single response-focused or mindfulness and combined techniques. We encourage researchers to include multiple downregulation mechanisms in their experiments. This may provide insights for further optimizing and tailoring treatment, including in combination with mindfulness strategies. Future experiments may for instance compare effects of response-focused trainings with or without mindful attention on addictive (brain) responses as mediated by 'downregulation' mechanisms. Second, future randomized controlled trials in both clinical and non-clinical samples are needed to examine longer-term effects of combined response-focused and mindfulness-based intervention treatments, while also paying attention to underlying neural and behavioural mechanisms of these longer-term treatment effects. These interventions may compare effects of prolonged response-focused training in daily life with MBIs in 2×2 randomized controlled designs. According to our model, and if supported by experiments, such a combined intervention would start with mindful momentary awareness meditation training to support response-focused trainings and then elaborate training further with specific decentering strategies and combined present moment awareness and acceptance training, as is cultivated in MBIs like MBSR and MORE. Ecological momentary assessment measures of mindfulness, stress-regulation, affect, craving and further addictive responses should be measured during different stages of the intervention. Neuroimaging data should be measured at least before and after intervention, but we encourage researchers to include additional in-between neural measures as this may reveal further insight into the question whether changes in brain function may drive, or be driven by, reduction in addiction outcomes. Although fMRI studies examining effects of MBIs in people with substance use dependence mostly used drug cue reactivity tasks (Lorenzetti et al., 2023), and recommendations for such studies have been reported (Ekhtiari et al., 2022), future neuroimaging studies should also examine the other principal ways in which MBIs may impact the course of addictive disorders, including decreasing stress perception, as mentioned (Rosenthal et al., 2021).

Neural studies are also required to examine if and how trait mindfulness moderates how MBIs affect brain function in substance use disorders (Lorenzetti et al., 2023) and other addiction-related behaviours, including in combination with response-focused strategies. Moreover, neural mediation studies should not only focus on differences in specific brain areas after (combined) response-focused and mindfulness treatments, as mostly been the case thus far. They should also focus on dynamic neural connectivity between areas, as addiction is often conceptualized as impacting individual differences in reward sensitivity and cue-reactivity along with weakened cognitive control or self-regulation (Volkow et al., 2019). Moreover, these studies should examine stress-related and drug-cue related dopamine release in mesolimbic brain areas (Baik, 2020; Cofresí et al., 2019) to further increase insights into specific underlying differential neural mechanisms based on genetic differences. Finally, they should further examine specific links with the proposed mechanisms of change (i.e., attention, different downregulation and emotional reactivity mechanisms). This is considered crucial, as it can further increase insights into addiction-specific, task-specific and target-group specific effects and ultimately pave the way for more tailored treatment approaches. In addition, it may reveal further insights into functions of specific brain areas, and, as such, provides important implications for the field of neuroscience.

4.2. Concluding remarks

This review adds to the existing literature by providing a recent overview of the most prominent neurocognitive effects of CBM trainings, cue-exposure therapy and mindfulness interventions for targeting addictive responses. It highlights the key insights that have stemmed from cognitive neuroscience and brain imaging research and combines these with insights from behavioural science in building an innovative conceptual model integrating mindfulness with cognitive bias modification or cue-exposure interventions. This model furthers our understanding of whether and how mindfulness strategies may i) facilitate or add to the induced response-focused effects decreasing cue-induced craving, and ii) further weaken the link between craving and addictive responses. The conceptual model presented in this review is necessarily a simplification, however, it provides a specific theoretical framework to deepen our understanding of how mindfulness strategies and CBM or cue-exposure interventions can be combined to greatest effect. This is important in both suggesting a roadmap for future research, and for the further development of clinical interventions, including among disadvantaged populations who may display enhanced procedural learning but lower executive control (Ellis et al., 2022; Ellis et al., 2017; Frankenhuis and Nettle, 2020) and might particularly profit from interventions targeting stimulus-response associations.

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