Gaming Disorder: How to Translate Behavioral Neuroscience Into Public Health Advances

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Abstract

Purpose of Review Gaming disorder (GD), meanwhile classified as a mental disorder in both DSM-5 and ICD-11, is a current public health issue. Theoretical models assume core psychological processes, such as cue reactivity, craving, reward processing, decision-making, cognitive biases, inhibitory control, and stress relief, to be crucially involved in the development and maintenance of GD. This review summarizes neuroscientific findings on these processes in the context of GD as well as treatments and intervention programs addressing these processes.

Recent Findings We identified overlaps regarding the involvement of neural structures and networks related to psychological processes which may be targeted by public health programs. Complex interactions between executive control, salience, reward, and habit networks are crucially linked to processes involved in GD and public health programs respectively.

Summary We point at the difficulties of making one to one assignments of neural networks to psychological processes or interventions. Furthermore, new treatment and prevention programs of GD are discussed pointing at possible future directions for neuroscientific research and treatment programs for GD.

Keywords Videogaming · Prevention · Intervention · Neurobiology

Introduction

With the inclusion of the diagnostic criteria for Internet gaming disorder in section III of the fifth edition of the *Diagnostic and Statistical Manual of mental Disorders* (DSM-5) and the inclusion of gaming disorder (GD) in the 11th revision of the *International Classification of Diseases* (ICD-11), problematic online gaming behavior has been officially acknowledged as a disorder to which particular attention should be paid with regard to public health. Core features of GD are diminished control over the behavior, priority given to gaming, and

continuation of gaming despite adverse consequences of gaming resulting in functional impairment [1]. Prevalence estimates vary substantially across studies but are considered as average about 9.97% (SD = 8.41; calculated using data from the systematic review by Darvesh et al. [2]) of the general population and are considered widely similar for adults, adolescents, and children. Although the variance in prevalence estimates can be explained by methodological and cultural aspects, they show impressively that GD is a serious public health issue and that there is a need for the use and development of interventions and preventions across all ages.

Psychological processes that may be the basis for diminished control over gaming and the continuation or escalation of the behavior despite the experience of negative consequences [3] have been described in theoretical models on GD [4, 5]. Core processes assumed by both models are reward processing, decision-making, cue reactivity, craving, inhibitory control, cognitive biases, and stress relief (coping). Perceived internal and external cues are assumed to trigger conditioned cue reactivity and craving responses in terms of special attention and strong urges to play videogames. These cravings may promote decisions toward gaming (despite knowledge of potential negative side effects), especially in

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case the ability to control or inhibit affective “approach” responses toward tempting stimuli is low. The performance of the (in later stages habitualized) gaming behavior may result in rewarding outcomes in which its processing may lead to the experience of gratification or compensation. It is assumed that the experience of reward (or reduced negative mood) makes future gaming behavior more likely and, over time, may lead to distorted anticipatory reward processing in terms of cognitive biases and (maladaptive) coping styles, which in turn affect the perception and attention toward addiction-related cues. This “vicious cycle” is assumed to consolidate over time leading to (stimuli specific) reductions in inhibitory control and decision-making as well as increases in cue reactivity, craving, reward sensitivity, and cognitive biases [4, 5]. Definitions of the central processes are summarized in Table 1.

A central assumption within the models is that these psychological processes do not stand alone but interact with each other. For example, diminished inhibitory control and decision-making abilities may increase the experience of craving in situations confronted with internal or external cues. Another example is that current stressors may act as a

moderating factor that decreases control and increases affective responses (e.g., craving). Some of these psychological processes are more strongly connected, often occur simultaneously, and cannot be clearly distinguished from one another. For example, craving is often a result of the physiological, emotional, and cognitive response to conditioned stimuli of cue reactivity [9]. Another example is that reward processing is most often conceptualized as a part of decision-making [12]. Therefore, these processes are often implicitly measured together in experimental studies.

Research on substance use disorders indicates that the interactions between these psychological processes may be based on shared neural correlates and interactions between neural networks [13–15]. Similarly, a current review indicates that also in non-substance addictive behaviors including GD, similar networks are involved in different psychological processes [16]. For example, networks such as executive control (dorsomedial, dorsolateral, and ventrolateral prefrontal cortex), salience (insula, dorsal anterior cingulate cortex, inferior parietal lobulus), reward (amygdala, ventral striatum, orbitofrontal cortex, and rostral anterior cingulate cortex), and habit (caudate nucleus and putamen networks) were

Table 1 Definitions of core psychological mechanisms and their proposed involvement in the development and maintenance of gaming disorder

Psychological mechanism	Definition in the context of addictive behaviors	Mechanisms potentially involved in GD
Reward processing	Neural/behavioral response to a (potentially) rewarding stimulus. Comprises processing of reward-related decision outcomes and anticipatory reward processing in terms of expectation of gratification (see “wanting” and “liking” [6]). Also associated with cue reactivity and individual reward sensitivity.	Altered reward processing such as increased reward sensitivity toward gaming rewards in early stages of GD [4, 5]. In later stages, there may be a shift from gratification to compensation [4].
Decision-making	Preference for and choice of immediate reward [5].	Individuals with GD may prefer short-term rewarding gaming behavior despite negative long-term consequences [4, 5] resulting in repeated gaming behavior.
Cue reactivity	Physiological, emotional, and cognitive response to conditioned addiction-related stimuli [7, 8].	Conditioning processes linking gaming behavior to reward experience may result in increased responses to gaming-related cues. Cue reactivity may trigger craving, cognitive biases, and reductions in control over gaming behavior [4].
Craving	Intense and urgent desire to behave in a specific way (e.g., taking a substance, playing an Internet game). Is potentially the consequence of cue reactivity [9].	Craving may increase during the development of GD. Together with decreased inhibitory control and decision-making abilities, craving may result in diminished control over gaming behavior [4, 5].
Inhibitory control	Cognitive functions that enable the inhibition of prepotent courses of action [10].	May be diminished or worsen during the development of GD especially when gaming cues are present [4, 5]. Resulting in an imbalance between cue reactivity/craving and control functions.
Cognitive biases	Umbrella term for different forms of biases and cognitive distortions. These automatic processes, such as attentional bias and approach or avoidance biases, occur when being confronted with addiction-related stimuli [11•].	Rewarding effects of gaming behavior may lead to cognitive biases, resulting in automatic processing of gaming-related stimuli. Cognitive biases may enhance cue reactivity and craving [4].
Stress response (coping)	Physiological response toward internal or external stressors, which evokes the development of coping strategies	Gaming behavior may relief from stress [5]. In addition, negative consequences resulting from gaming behavior may increase the experience of stress.

shown to be involved in processes of both inhibitory control and cue reactivity/craving (see Fig. 1a for a more detailed description of networks).

In addition, these core psychological processes have been identified as starting points for GD interventions [5, 17]. It is assumed that by treating one specific psychological process, also other psychological processes may be affected due to the existing interactions. For example, interventions aiming at increasing executive control (including inhibitory control) and decision-making capacity may reduce the experience of craving and thereby the specific gaming behavior [5]. This points to the importance of insights from the neurobiology of psychological processes involved in GD and findings on neural alterations affected by preventions and treatments for decisions on the use and development of public health programs.

The current review summarizes neuroscientific and behavioral findings on core psychological processes of GD to describe neural networks involved in these processes. Furthermore, we summarize findings from prevention and treatment studies with a special focus on neural alterations. We particularly focus on studies in the context of GD but we also included studies in which the term “Internet use

disorder” is used to describe multiple online behaviors including Internet GD. Furthermore, we will reference to findings from substance use disorders to highlight promising prevention and intervention programs that have not yet been evaluated in the context of GD. A more detailed description of psychological prevention and intervention approaches can be found in Table 2.

Reward Processing and Decision-making

Neuroscientific and Psychological Findings on Reward Processing and Decision-making in GD

Neural correlates of reward processing independent from decision making in GD has been investigated in only one study [41]. This study showed that individuals with GD and healthy controls responded similarly to monetary gains and losses. However, they report altered neural processing with regard to monetary losses within the caudate nucleus as part of the habit system.

Fig. 1 The figure summarized results reviewed in the current manuscript with regard to neural networks involved in psychological processes and public health programs of gaming disorder. **a** Neural networks and brain regions that are assumed to be involved in the development and maintenance of gaming disorder. The figure (**a**) was modified from Figure 1 in Antons et al. [16]. Reprinted from Antons, S., Brand, M., and Potenza, M. N. (2020). Neurobiology of cue reactivity, craving, and inhibitory control in non-substance addictive behaviors. *J Neurol Sci*, 415, 116952, Copyright (2020), with permission from Elsevier. **b**

Preliminary findings on psychological processes and public health advances and their associated neural networks (represented by colored dots). Amyg, amygdala; Caud, caudate nucleus; dACC, dorsal anterior cingulate cortex; dlPFC, dorsolateral prefrontal cortex; dmPFC, dorsomedial prefrontal cortex; Ins, insula; IPL, inferior parietal lobe; OFC, orbitofrontal cortex; Put, putamen; rACC, rostral anterior cingulate cortex; vlPFC, ventrolateral prefrontal cortex; VS, ventral striatum

Table 2 Description of psychological prevention and intervention approaches included in the current review

Prevention/intervention	Description	Addresses	Applied in gaming disorder
Cognitive behavioral therapy (CBT)	Seek to help recognizing behavioral patterns and cognitions that contribute to maintenance of the addictive behavior. Learning and implementing skills and strategies to change these patterns of behavior [18]. Often includes different modules addressing, e.g., identification of triggers and discrimination of emotional states, improving decision-making and providing alternative options, reducing automatic thinking and cognitive distortion, enhancing self-control and stress reduction.	RP/DM CR/C IC SR	[19–23]; also see [24•, 25]
Virtual reality therapy	Includes relaxation, simulation of a high-risk situation, and sound-assisted cognitive reconstruction. Applied with a virtual reality system and for 8 sessions [19].	CR/C	[19]
Craving behavioral intervention	Includes aspects of recognizing subjective craving, reduction of craving, enhancing self-monitoring and control for craving, as well as coping skill training.	CR/C	[26–29]
Development of self-control skills	Part of both prevention and intervention. May include skill training on self-control and self-regulation (monitoring, limit setting, time management, motivation) [30•, 31]. Is often part of CBT.	DM IC	[30•, 31]
Mindfulness-based programs	Often includes modules on mindful awareness of gaming behavior, coping with negative and enhancement of positive affective states using mindfulness. Increasing craving awareness and use of mindfulness to cope with craving. Stress reduction, promoting acceptance of unwanted thoughts and distressing experiences. Practicing of love-kindness meditation, developing a plan to use mindfulness skills [32]. Is sometimes combined with other therapy approaches such as reality therapy [33] and CBT.	CR/C IC SR	[32–34]
Stress reduction	Prevention programs for GD often include modules teaching stress management [30•]. Stress reduction (e.g., through meditation or mindfulness relaxation) and the development of stress coping strategies are often part of CBT and mindfulness-based therapies.	SR	[19, 22, 23, 30•, 32–34]
Working memory training	Tasks in which individuals are asked to integrate, manipulate, suppress, and prioritize information [35]. Aims at increasing working memory capacity or response time to stimuli that should be remembered [36, 37]. Different approaches of non-computerized, computerized, and also mobile applications.	DM C IC	Pending
Inhibitory control training	Inhibitory control is typically trained on a go/no-go task, stop-signal task, or Stroop task. In the context of addictive behaviors, these inhibitory control tasks are often paired with cues related to the specific addictive behavior [38].	IC	Pending
Cognitive bias modification	Cognitive bias modification trainings aimed at changing disorder-specific maladaptive cognitive motivational biases by influencing disorder-specific impulsive processes [39].	CB	[40]

C craving, CB cognitive bias, CR cue reactivity, DM decision-making, IC inhibitory control, SR stress response, RP reward processing

When investigating reward processing in the context of decision-making, results indicate that symptoms of GD and Internet use disorders (including gaming) are associated with riskier decision-making behavior [42, 43•]. This includes a stronger preference for smaller sooner over larger later rewards (i.e., have a higher discount rate) [44, 45] and weaker (i.e., riskier) performance on gambling tasks that provide objective risk information [46, 47]. In decisions under ambiguity, findings are less clear which suggests that decision-making performance in this type of situations might not be indicative of GD [48].

On neural levels, the preference for smaller sooner rewards (delay discounting) was associated with alterations in executive control and reward network activity in GD [49]. In risky

decision-making tasks, patients with GD displayed increased activity in the left striatum, right inferior frontal gyrus, and insula. Decreased activities were found in the left superior and inferior frontal gyri and in the right precentral gyrus. Overall, the findings are in line with the results of the meta-analysis by Yao et al. [50•] showing that GD was associated with increased activity in the reward, salience, and executive control networks in the domains of reward and “cold” executive functions. Furthermore, findings on the functional activity in different phases of the decision-making process suggest that individuals with GD (compared with those without) show weaker neural responses in executive control (dorsolateral prefrontal cortex) and salience networks (inferior parietal lobule) during the evaluation of potential losses while they show

stronger neural responses within the reward network during the processing of rewards [51].

The aforementioned findings indicate a potential neurobiological basis for why individuals suffering from GD continue gaming despite the experience of negative consequences, i.e., they have a weaker sensitivity to risk and a higher sensitivity to rewards. These neural mechanisms involving the executive control, salience, reward, and habit networks may be promising targets for developing treatments of GD [51].

How to Include Techniques Improving Decision-making Into Prevention and Treatment

Given that young people already have a risk to develop problematic gaming behaviors, prevention programs are often applied at schools. These programs address reward processing and decision-making by teaching alternative activities and goal setting, as well as understanding of media and self [30•]. Similarly, parts of cognitive behavioral therapy (CBT) address impulsive decision-making [19, 20]. The educational programs may improve decision-making in the context of gaming, although an empirical validation of this hypothesis is pending.

A combined reality therapy and mindfulness meditation program has been shown to reduce delay discounting but had no effect on risky decision-making in GD [33]. CBT has been shown to increase connectivity between the posterior cingulate cortex, cerebellum, thalamus, and occipital lingual gyrus in individuals with GD [19]. Because of the multifaceted nature of CBT, the neural mechanisms directly linked to specific techniques remain poorly understood—also for substance use disorders [18]. It may be assumed that modules on reward processing and decision-making may alter neural networks related to the processing of rewarding stimuli and executive control, which is suggested by a systematic review on neural mechanisms of CBT in depression [52]. More research is needed to understand the effects of specific interventions and prevention programs on decision-making in GD.

There is a common agreement for a relationship between working memory and decision-making [53]. Trainings increasing working memory capacity are therefore assumed to have a positive effect on decision-making. An examination of the effects of working memory training in GD is pending. However, studies reported improvements in delay discounting [54], craving [55], impulsivity, and self-regulation [56] following a working memory training in individuals with substance use disorder. In general, neural associations of training-induced improvements of working memory have been identified within executive control, salience, and habit networks [57]. However, due to a small number of studies and methodological caveats by investigating neural correlates of working memory training, these associations should be interpreted cautiously.

Cue Reactivity and Craving

Neuroscientific and Psychological Findings on Cue Reactivity and Craving in GD

There is strong evidence that individuals with GD experience increased cue reactivity and craving on a subjective level [58]. Meta-analyses [59, 60•] on the neurobiology of cue reactivity in addictive behaviors including GD showed that this mechanism is probably associated with hyperactivity of the precuneus, the cingulate cortex, the precentral gyrus, the right inferior frontal gyrus, the superior temporal gyrus, and the caudate nucleus—thus, within executive control, salience, and habit networks—and hypoactivities in the insula (salience network) and the postcentral gyrus. The results were partly inconsistent across the two meta-analyses as they differ regarding the inclusion of studies. Beyond cue reactivity, the first results indicate that also craving may be associated with increased activity in reward, salience, and executive control network, and habit networks in GD [61–64]. The results should be interpreted as preliminary because they base on only few studies with small sample sizes [16].

How to Include Cue Reactivity Management and Craving Reduction Techniques Into Prevention and Treatment

Since craving may develop in later stages of the development of GD [4], it is often addressed in treatment interventions and less in preventions before the onset of clear symptoms. The identification of triggers and discrimination of emotional states have been parts of CBT which reduced symptoms of GD and also gaming time [65]. Cue reactivity and craving have been also targeted in parts of virtual reality therapy and a combined CBT and bupropion treatment, which resulted in reductions of symptoms [19, 20]. As mentioned earlier, the exact mechanisms of CBT efficacy and related mechanisms are poorly understood since modules often differ [18]. It may be assumed that modules addressing cue reactivity and craving may specifically influence networks implicated in these mechanisms such as executive control, salience, reward, and habit networks [16, 59].

Mindfulness-based interventions could also decrease the level of craving and symptom severity of GD [32, 34]. Garland and Howard [66] reviewed the effects of mindfulness meditation intervention components on behavioral and biological mechanisms in the addiction context. They conclude that mindfulness-based techniques may amplify executive control network activities, increase fronto-striatal connectivity, decrease the reactivity of the salience network, and improve autonomic regulation. These neural alterations on executive control, reward, salience, and habit networks may result in decreased cue reactivity and craving as well as reduced

stress reactivity. Furthermore, it may result in restructuring of reward processing and increased executive function. Thus, mindfulness may not only address cue reactivity and stress reduction but also further behavioral mechanisms relevant for the treatment of GD.

The craving behavioral intervention specifically includes aspects of craving perception, detection, and coping with craving [29]. Studies indicate positive effects in terms of decreases in symptom severity, perceived craving, and game play time in GD [26, 27]. During confrontation with cues, the intervention altered reactivity within the anterior insular as part of the salience network [29]. However, this increase in insula activity did not correlate with changes in craving [29]. The same research group investigated alterations in seed-based connectivity resulting from the intervention. Liu et al. [67] found increased connectivity between the default-mode and salience network, Zhang et al. [27] found decreased connectivity between the ventral striatum (reward network) and inferior parietal lobule (salience network), and Zhang et al. [28] found decreased resting-state connectivity between orbitofrontal cortex (reward network) and hippocampus, and between posterior cingulate cortex and the supplementary motor cortex. These results indicate that a specific craving intervention may effectively alter processing and connectivity within and between salience, reward, and executive control networks. Results should be seen as very preliminary and much more research is needed to understand the complexity of neural correlates of craving.

Inhibitory Control

Neuroscientific and Psychological Findings on Inhibitory Control in GD

Meta-analytical results point at significant impairments in inhibitory control on a behavioral level in participants with GD [68] and Internet use disorders [43, 68]. The meta-analysis by Zheng et al. [60•] identified hyperactivities within the superior temporal gyrus, the precuneus, the caudate nucleus (habit network), and the cingulate cortex (salience/reward network) as well as hypoactivities in the inferior frontal gyrus (executive control network) in individuals with GD compared with healthy controls during inhibitory control tasks. It is assumed that inhibitory control is particularly diminished when individuals are confronted with gaming-specific cues [4]. The tripartite neurocognitive model by Wei et al. [69] suggests that in such situations, the reward system overwrites the control mechanisms of the executive control system, which is amplified by the insula (salience network). Few studies investigated the neural correlates of this stimuli-specific inhibitory control in GD; however, there is first evidence for altered function of

executive control, reward, salience, and habit networks in GD and further non-substance addictive behaviors [16].

How to Include Inhibitory Control Techniques Into Prevention and Treatment

Prevention programs for students often include education and skill training on self-control and self-regulation (limit setting, time management) [30•]. As a result, e.g., Apisitwasana et al. [31] found that training focusing on the enhancement of self-regulation of gaming behavior has positive effects in terms of decreasing symptoms of GD and increased self-regulation 3 months post-intervention. In this program, teachers and parents were involved to lead activities and to help maintain consistency. Also, further educational and skill training preventions showed positive effects on self-regulation and self-restraint of using the computer [30•]. It is possible that these changes in self-regulation may positively affect connectivity between the hippocampus and ventromedial prefrontal cortex [70]. However, this effect needs to be investigated in the context of GD.

The reduction of impulsivity, exposure training, and learning stopping techniques are parts of some cognitive behavioral programs that address inhibitory control. These treatment programs have been shown to be effective with regard to reductions in symptom severity of GD, impulsivity, and game play time [22, 23, 65]. Similarly, the combined reality therapy and mindfulness meditation approach by Yao et al. [33] specifically addresses impulsivity and showed to be effective in reducing symptoms of GD. CBT and mindfulness-based techniques may counteract neural alterations within executive control, salience, reward, and habit networks [52, 66, 71]; however, evidence from GD research is still pending.

Lee et al. [72] used transcranial direct current stimulation as a neuromodulatory technique to reduce symptoms of GD and to increase self-control in a pilot study. The stimulation over the dorsolateral prefrontal cortex as part of the executive control network resulted in decreased symptoms and game play time as well as increased self-control. This may be a promising result for the development of interventions based on non-invasive neurostimulation which has been shown to reduce craving by increasing prefrontal function and cognitive control in substance use disorders [73]. A further promising technique to increase inhibitory control may be inhibitory control training. In a meta-analysis, Jones et al. [38] report a significant decrease in food or alcohol consumption following an inhibitory control training. Its effects on neural structure and function are still unresolved. In general, preliminary findings indicate structural alterations within several regions of executive control network in children and adolescents following inhibitory control training irrespective of the addiction context [74]. Future studies may show the mechanisms potentially

underlying positive effects of inhibitory control trainings in individuals with GD.

Cognitive Biases

Neuroscientific and Psychological Findings on Cognitive Biases in GD

Recently, evidence on cognitive biases in Internet use disorders and GD were reviewed [11•]. Four out of five studies investigating cognitive biases in GD report increased attentional and approach biases toward gaming stimuli. On a behavioral level, Zhang et al. [75] did not find these effects. However, brain regions involved in selective attention, visual processing, working memory, and cognitive control including the parts of the salience and executive control networks showed higher activity in individuals with GD as compared with control participants. Using independent component analysis, Wang et al. [76] report for the same sample increased functional connectivity between the temporal gyrus and the frontal gyrus as well as decreased connectivity between the posterior cingulate cortex, the temporal gyrus, and the frontal gyrus in individuals with GD compared with control participants. In substance use disorders, cognitive biases have been associated with an altered function within the reward, executive control and salience networks [77] which is consistent with the results on GD showing altered function within executive control and salience networks. Regarding GD, further evidence is needed to understand the neural mechanisms of cognitive biases.

How to Include Techniques to Modify Cognitive Biases Into Prevention and Treatment

The CBT for GD applied by Han et al. [22] includes one session on automatic thinking and cognitive distortion which specifically addresses cognitive biases. The intervention showed to be effective with regard to reductions in symptom severity and impulsivity; however, its effects on cognitive biases remain unclear.

Cognitive bias modification is an approach to directly address automatic biases. Only one study investigated the effects of a cognitive bias modification with regard to approach biases in GD [40]. In this study, individuals showed less approach tendencies toward gaming cues after one session of cognitive bias modification. Furthermore, the training reduced craving and intentions to game play. First, studies on neural correlates of cognitive bias modification in different psychiatric disorders indicate increases in executive control network activity and reductions in reward network activity [39]. However, these results are very preliminary and similar effects for addictive behaviors and GD are questionable.

Stress Response

Neuroscientific and Psychological Findings on Stress in GD

Studies report the symptom severity of GD to be associated with increased perceived stress [78–83] and emotional trauma or maltreatment during childhood [84, 85]. Furthermore, Canale et al. [79] could show that stress was positively correlated with hours of game play per week. As known from substance use disorder neuroscience, altered stress processing may be associated with neural alterations in the brain's stress system which includes executive control and reward networks [86]. A further study by Kaess et al. [87] showed attenuated cortisol response and more negative affect to acute stress in individuals with GD. However, results could not be replicated with hair hormone levels for cortisol [87, 88]. These results are based on small sample sizes and should be interpreted cautiously.

As proposed for substance use disorders, interactions between response toward stressors and increased craving may be explained by interactions between the stress and reward system that lead to mechanisms of negative reinforcement and the increase in motivation to behave in a specific way [86, 89]. Consistent with this assumption, motives to play online games relating to coping and escapism as well as maladaptive cognitions relating to overvaluing game rewards were identified as predictors for GD [80, 90, 91].

How to Include Stress Reduction Techniques Into Prevention and Treatment

Stress reduction and stress control have been deployed as parts of selective intervention programs for GD and Internet use disorder to school students [30••]. In addition, reduced resilience and self-control have been identified as mediators between stress and problematic gaming behavior [79, 92], and thus might have protective effects.

Stress reduction and the development of coping strategies are often a part of CBTs. In primary studies, testing the efficacy of CBT including stress reduction techniques and the development of coping strategies have shown to decrease symptoms of GD [19, 22, 23]. Also, programs including mindfulness meditation address stress reduction and coping. In two studies, effects on symptom severity of GD were shown [32, 34]. However, the program had no effect on cognitive coping styles [32].

These effects may be mediated by increased amygdala habituation to stress and downregulation of emotions through executive control and salience networks [93]. In addition, subjective controllability of stress may have positive effects on the development of executive control, reward, and salience networks in adolescents [94].

Conclusion

The review showed that research on the neuroscience of GD is still in its infancies; results and interpretation of results should be taken cautiously. Yet, the increasing findings on associations between psychological and neural mechanisms and how these could be counteracted by preventions and interventions may be used to direct and advance the development of public health programs for GD.

Overall, complex interactions between neural networks such as the executive control, salience, reward, and habit networks are the basis for different psychological mechanisms in GD. Preventions and interventions address these psychological and neural mechanisms to varying degrees. Figure 1b shows which neural networks have been associated with psychological mechanisms and public health programs in previous studies. It becomes clear that a one to one assignment of neural networks to psychological processes or interventions may be impossible.

Systematic reviews on treatment approaches for GD show that CBT has been the intervention most often applied in GD and which showed the highest efficiency [24•, 25]. Although also family-based interventions and counseling programs as well as pharmacological treatments were efficient in reducing symptoms, CBT may be beneficial compared with other approaches [24•, 25]. Again, it has to be emphasized that much more research is needed to understand all the mechanisms involved in the development and treatment of GD. Nevertheless, it is possible that the effectiveness of CBT and similar treatments addressing multiple psychological mechanisms results from their complexity and from their effect on multiple neural networks.

In addition, less is known about the degree of involvement of different psychological mechanisms and neural alterations on an individual level. Future research may focus on the identification of biomarkers of psychological mechanisms based on neural, structure, and function as well as genetics. The identification of these biomarkers may allow to identify which intervention has an effect on whom and under which circumstances [71]. This would allow the development of more effective and possibly also personalized preventions and treatments.

Code Availability Not applicable.

Authors' Contributions SA and MB generated the focus and the structure of the article, SA, SMM, and ML performed the literature search, SA, SMM, and ML drafted the manuscript, MB supervised the writing of the manuscript and critically revised the work. The final draft was discussed with and approved by all co-authors.

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Compliance With Ethical Standards

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- Of major importance

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