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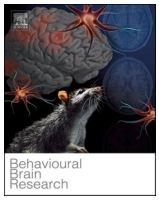

Decoding the neural correlates of social cognition and emotion recognition in cannabis users: A systematic review of neuroimaging studies

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ABSTRACT

Social factors significantly influence the initiation and progression of cannabis use and cannabis use disorder. Although cannabis is the most widely used drug globally, its social cognitive aspects and neural correlates have rarely been studied. To evaluate the findings to date and to guide future research, this systematic review assesses neuroimaging evidence on the associations between long-term cannabis use, social cognition, and emotion recognition. Findings from 8 studies on social cognition suggest an increased neural response to social influence and a decreased neural sensitivity to social exclusion, psychosocial stress, and social reward. However, these results should be interpreted with caution, and further replication is necessary due to the limited number of studies in each area. The findings from 21 studies on emotion recognition remain largely inconsistent. Specifically, regarding the amygdala, cingulate cortex, and frontal areas, findings vary, with certain studies reporting increased activity in response to affective stimuli in cannabis users compared to controls, while other studies reported the opposite effect. These effects could be caused by methodological and sample differences across the studies on emotion recognition. Overall, the functional implications, the causal relationship with use, and the role of individual user characteristics, such as the severity of CUD symptoms, gender, and age remain unclear. Future research should involve larger, more diverse samples and specifically target individuals with CUD. Especially, longitudinal studies focusing on social motivational processes, the brain, and the roles of age and gender as potential moderators could provide valuable insights.

1. Introduction

The most reliable predictor of cannabis use during adolescence is the proportion of substance using friends [1,9]. Furthermore, perceived peer cannabis use has predicted both the onset and progression of use [12]. During adulthood, those who seek treatment for a cannabis use disorder (CUD) generally report decreased psychosocial functioning as well as decreased emotional relief efficacy [29,50]. Despite being one of the most widely used drugs in the world (4.3 % of the global adult population in 2021; [74]), the social cognitive aspects of cannabis use have seldom been studied [56]. Moreover, the neural substrates that have commonly been associated with substance use disorders (SUDs) show significant overlap with those associated with social cognition and emotion recognition (Fig. 1). The goal of this systematic review is to evaluate the evidence from neuroimaging studies that focus on the associations of long-term cannabis use with social cognition and emotion recognition (i.e., an important building block of social cognition). To address this, we evaluated studies that included any form of social cognitive or emotion recognition measure in relation to a neuroimaging method.

Social cognition is a comprehensive term that refers to various cognitive functions necessary for individuals to engage with their social environments. It involves the mental processes used to perceive, interpret, and respond to social information [2,56]. This includes but is not limited to social influence, theory of mind, empathy, psychosocial stress, and social reward [56]. Emotion recognition, sometimes called emotion perception or affect recognition, has been used as an umbrella term for the ability to interpret and scale emotions from faces, scenes, words, and situations [3,56]. It is an important facet of social cognition and was therefore also included in this review.

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Social cognition and emotion recognition play an important role in both the onset and progression of SUDs [55,56,78], as well as in treatment outcomes [17]. In the context of cannabis use, behavioral studies suggest an association between cannabis use and recognition impairments in both speed and accuracy across a range of emotions. Platt et al. [53] found that cannabis users were significantly slower at recognizing, sad, angry, happy, and neutral emotions compared to controls. Hindocha et al. [33] further expanded on these findings, demonstrating decreased accuracy in recognizing all emotions except for surprise in users compared to controls. Bayrakçı et al. [4] found emotion recognition deficits even in one-month abstinent users, primarily in the recognition of negative emotions. These results indicate substantial differences in emotion recognition between cannabis users and controls across a wide range of emotions, suggesting that different underlying neurological processes could be present.

To the best of our knowledge, two narrative reviews linking the brain, cannabis use, social cognition, and emotion recognition have been conducted previously. Gilman [22] focused specifically on social influence and suggested that underlying brain regions may respond differently in cannabis users compared to non-using controls. However, Gilman [22] explores the association between social influence and substance use more broadly, highlighting brain regions commonly linked to peer influence by discussing studies that were conducted outside the context of cannabis use. MacKenzie and Cservenka [42] focused explicitly on emotion recognition and found differences in neural functioning between cannabis users and non-using controls, particularly in the subcortical regions. In the social cognitive domain, several recent studies have been conducted focusing specifically on social reward, psychosocial stress, and empathy. Despite the expanding body of research, these studies have not been comprehensively reviewed [49,86,87]. Moreover, a systematic review that encompasses social cognition, emotion recognition, cannabis use, and the brain remains to be conducted.

In the present systematic review, we build upon previous research by addressing the following question: do the brain regions associated with social cognition and emotion recognition respond differently to social stimuli and situations in cannabis users compared to non-using controls? To address this, we systematically reviewed studies that directly compared cannabis users and non-using controls. By integrating evidence from studies on social cognition and emotion recognition, we aim to provide a comprehensive overview that offers valuable insights into the role of social factors in long-term cannabis use and cannabis use disorder (CUD), which could prove useful for therapeutic applications.

2. Methods

2.1. Search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed [46] and the search strategy and inclusion criteria were preregistered (https://www.crd.york.ac.uk/prospero/; CRD42023459685). The initial literature search was conducted in September 2023 in Cochrane, Embase, Medline, PsycInfo, and Web of Science Core Collection using terms related to cannabis, social cognition, emotion recognition and neuroimaging using a combination of Boolean operators (e.g., "AND", "OR"; complete search syntax can be found in Appendix A). A search update was performed in August 2024, using the same search strategy to ensure that the most recent studies were included.

2.2. Inclusion criteria

Studies were included if they contained 1) any experimental or self-report measure of social cognition, 2) a comparison between different groups engaging in different degrees of cannabis use (e.g., control, recreational, dependent) and 3) any form of neuroimaging (e.g., fMRI, PET, EEG, fNIRS). Studies that included assessments of cannabis use, social cognition, and emotion recognition but primarily focused on co-morbid psychiatric diagnoses other than a CUD were excluded (e.g., Psychosis). Furthermore, since the focus of this review is primarily on the social neurocognitive factors associated with prolonged cannabis use, studies that only focused on acute cannabis intake were also excluded.

2.3. Study selection and extraction

Titles and abstracts were screened in a blinded review by two authors (CR and MM) in the first phase and articles that clearly did not meet the inclusion criteria were excluded. In the second phase, a blinded full-text assessment of the remaining articles was conducted by two separate reviewers (CR and MM) to determine which articles would be included according to the predefined inclusion criteria. Potential discrepancies

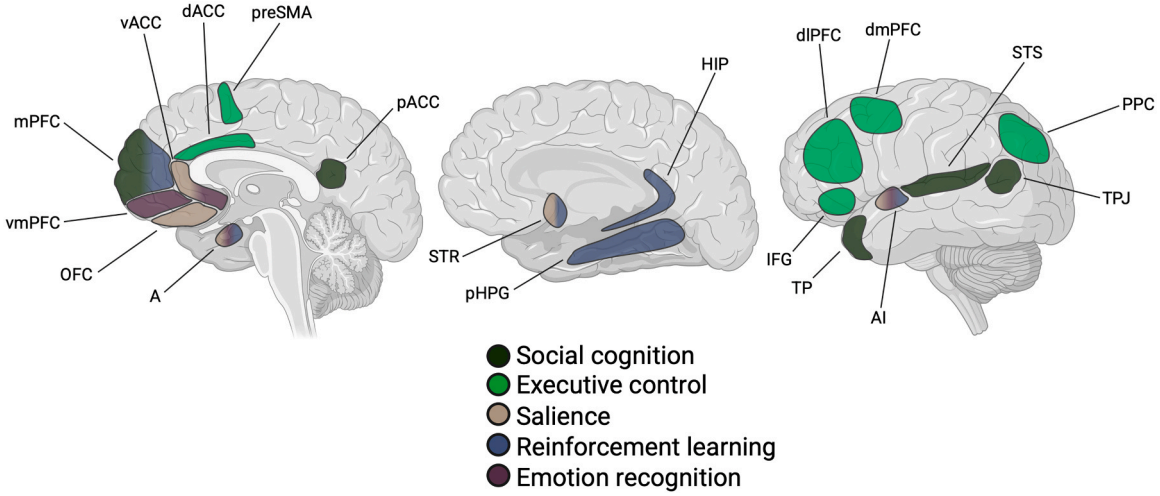

Fig. 1. Brain networks implicated in risk and resilience to substance use disorders, social cognition, and emotion recognition. **A**: Amygdala; **AI**: anterior insula; **dACC**: dorsal anterior cingulate cortex; **dlPFC**: dorsolateral prefrontal cortex; **dmPFC**: dorsomedial prefrontal cortex; **HIP**: hippocampus; **IFG**: inferior frontal gyrus; **mPFC**: medial prefrontal cortex; **OFC**: orbitofrontal cortex; **pACC**: posterior anterior cingulate cortex; **pHPG**: parahippocampal gyrus; **PPC**: posterior parietal cortex; **preSMA**: pre-supplementary motor area; **STR**: striatum; **STS**: superior temporal sulcus; **TP**: temporal pole; **TPJ**: temporoparietal junction; **vACC**: ventral anterior cingulate cortex; **vmPFC**: ventromedial prefrontal cortex.

were discussed by the reviewing authors assisted by a third reviewer (KC) until consensus was reached. A detailed flow diagram of the screening process can be found in Fig. 2.

3. Results

3.1. Study search

The initial search resulted in 5316 records and 3171 studies remained after deduplication. After screening title and abstract, 78 articles remained for a full-text review. After full-text screening for eligibility, 29 studies were included. Characteristics of studies focusing on social cognition-related neural functioning and behavior (n = 8) can be found in Table 1. Characteristics of studies focusing on emotion recognition-related neural functioning and behavior (n = 21) can be found in Table 2. The frequency of cannabis use within the cannabis groups is briefly summarized in the results and further elaborated upon in the corresponding Table. Details concerning the characteristics of the control groups are also presented in the corresponding Table. The results section of this review presents evidence of differences in neural functioning between cannabis users and controls, associations between neural functioning and heaviness of use, and associations between neural functioning and behavior measures. Within-group differences are not discussed in the results section of this review; however, they have been summarized in the corresponding tables.

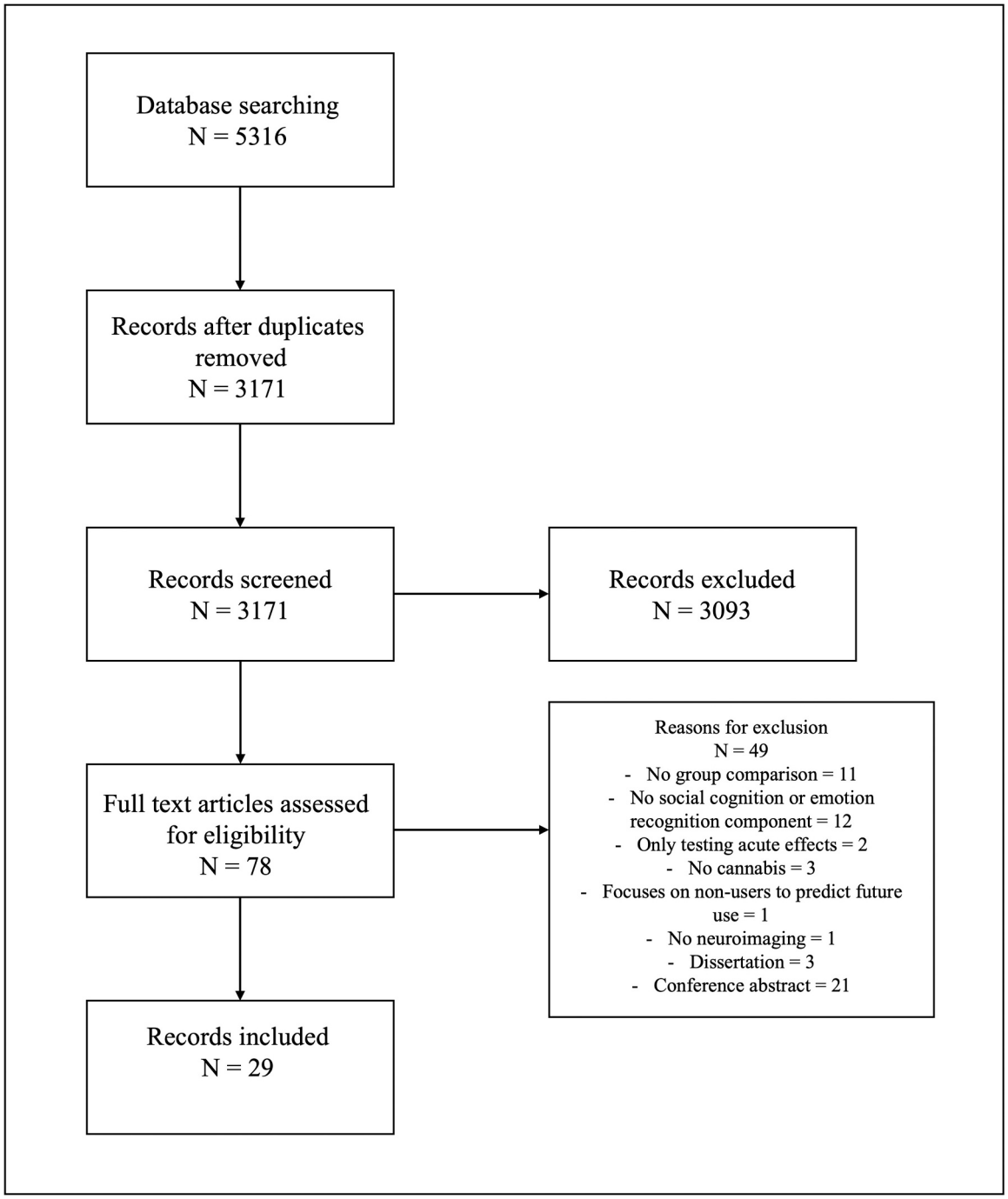

Fig. 2. PRISMA flow diagram detailing the screening process.

Table 1
Characteristics of studies comparing social cognition-related neural functioning between cannabis users and controls.

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
Gilman et al. [23]	Social exclusion	N = 42 (47.6 % male) CAN (>0 uses p/ week): n = 20 (20.6 ± 2.5 yrs) CON (<5 lifetime uses and no use in the preceding 3 months): n = 22 (21.5 ± 1.9 yrs)	Weekly: 5.4 ± 4.5 joints Days/week: 2.8 ± 1.5 Duration of use: 4.3 ± 1.7 yrs Age of onset: 16.3 ± 1.7 yrs	fMRI (ROI: r insula, vACC; whole-brain)	Cyberball social exclusion task	↓ R anterior insula and OFC in CAN vs. CON during exclusion vs. inclusion. ↑ L DLPFC, regions in parietal and occipital lobes in CON during inclusion vs. exclusion. ↑ R anterior insula, vACC, and lingual gyrus in CON during exclusion vs. inclusion. ↑ R frontal pole, r insula, r thalamus, regions in parietal and occipital lobes in CAN during inclusion vs. exclusion. ↑ vACC in CAN during exclusion vs. inclusion.	Not assessed	↑ vACC in CAN during social exclusion vs. social inclusion was positively correlated with peer conformity. ↑ vACC in CAN during social exclusion vs. social inclusion was positively correlated with total suggestibility scores.
Gilman et al. [24]	Social influence	N = 40 (50 % male) CAN (>0 uses p/ week and no CUD DSM-IV): n = 20 (21.2 ± 2 yrs) CON (<5 lifetime uses and no use in the preceding year): n = 20 (20.4 ± 1.7 yrs)	Weekly: 11.62 ± 9.76 joints Days/week: 3.96 ± 2.25 Duration of use: 6.34 ± 3.53 yrs Age of onset: 16.35 ± 2.24 yrs	fMRI (ROI: NAc; whole-brain)	Social influence task	*Behavior:* ↑ Response time in CON during hard trials vs. easy trials. *Brain:* ↑ Anterior cingulate and insula activation volumes in CAN vs. CON during choice after social influence vs. no social influence. ↑ Caudate in CAN during choice after social influence vs. no social influence. ↑ L frontal pole, l SFG, and l SPL in CAN vs. CON during choice after social influence vs. no social influence. ↑ NAc in CAN during choice when conforming vs. not conforming.	↑ NAc was positively correlated with joints p/week and joints p/occasion during choice when conforming vs. not conforming.	Not assessed
Gilman et al. [25]	Social influence	N = 43 (46.5 % male) CAN (>0 uses p/ week): n = 20 (20.6 ± 2.5 yrs) CON (<5 lifetime uses and no use in the preceding 3 months): n = 23 (21.6 ± 1.9 yrs)	Weekly: 6.6 ± 7.5 joints Days/week: 2.7 ± 1.2 Duration of use: 2.3 ± 1.5 yrs Age of onset: 18.3 ± 2.0 yrs	fMRI (ROI: caudate, NAc; whole-brain)	Social influence task	*Behavior:* ↑ Response time in CAN during non-conforming choices vs. conforming choices. *Brain:* ↑ Caudate, RCZ, IFG, and DLPFC in CAN during social influence vs. no influence. ↑ Occipital structures in CON during social influence vs. no influence. ↑ R caudate in CAN vs. CON during social influence vs. no influence.	Not assessed	↑ DLPFC in CON was positively correlated with response time. ↑ IFG in CAN was positively correlated with response time.
Mizrahi et al. [45]	Psychosocial stress	N = 25 (52 % male) CAN (>2 uses p/ week or CUD	Lifetime: 7859.85 ± 10566.6 joints	PET	Montreal Imaging Stress Task	≈ PHNO displacement in CAN vs. CON during psychosocial stress.	↑ PHNO displacement in the limbic striatum was	n.s.

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Table 1 (*continued*)

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
		DSM-IV): n = 13 (24.23 ± 4.9 yrs) CON (<6 lifetime uses): n = 12 (26.08 ± 3.8 yrs)	Duration of use: 9.23 ± 4.9 yrs Age of onset: 14.92 ± 1.3 yrs				positively correlated with duration of use.	
Olalde-Mathieu et al. [49]*	Empathy	N = 80 (65 % male) CAN (inclusion criteria unspecified): n = 46 (26.8 ± 5.0 yrs) CON (inclusion criteria unspecified): n = 34 (24.1 ± 5.0 yrs)	Lifetime use: 2200.4 ± 3427 joints Past 24-month use: 525.7 ± 432 joints Past 12-month use: 23.6 ± 20 joints Past 6-month use: 23.9 ± 21 joints Age of onset first use: 19.3 ± 4 yrs	fMRI (connectivity seeds: ACC)	Cognitive and Affective Empathy Test	*Behavior:* ↑ Emotion Comprehension Scale scores in CAN vs. CON. *Brain:* ↑ ACC-pre-posterior central gyrus and l anterior insula-ACC RSFC in CAN vs. CON.	Not assessed	n.s.
Roser et al. [59]	Theory of mind	N = 29 (100 % male) CAN (>2 uses p/ week during the preceding 2 years): n = 15 (26.5 ± 2.9) CON (0 lifetime uses): n = 14 (27.3 ± 3.5)	Weekly: 13.1 ± 7.4 joints Days/week: 5.2 ± 1.4 Duration of use: 8.5 ± 3.0 yrs	fMRI (whole-brain)	ToM task	↓ L parahippocampal gyrus, r precuneus, r cuneus, l SFG, l mFG, l MFG, STG, MTG, and insula in CAN vs. CON during ToM condition. ↑ L cuneus, r ACC in CAN vs. CON during ToM condition. ↑ PFC, ACC, PCC, TPJ, temporal cortex, and r insula in CON during ToM vs. non-ToM conditions. ↑ R PCC, precuneus, and temporoparietal regions in CAN during ToM vs. non-ToM conditions.	Not assessed	Not assessed
Zhao et al. [86]	Psychosocial stress	N = 51 (100 % male) CAN (CUD DSM-IV): n = 28 (25.54 ± 5.11 yrs) CON (<15 g of lifetime use): n = 23 (24.57 ± 3.55 yrs)	Lifetime: 2309 ± 1655 g Monthly: 23.61 ± 7.71 days Age of onset: 15.68 ± 2.82 yrs	fMRI (ROI: cingulate gyrus, insula, MFG, MOG, precuneus; whole-brain; connectivity seeds: precuneus)	Montreal Imaging Stress Task	*Behavior:* ↓ Accuracy in CAN vs. CON during psychosocial stress condition. *Brain:* ↓ Precuneus activity in CAN vs. CON in psychosocial stress condition. ↑ Precuneus-SFG stress functional connectivity in CAN vs. CON in psychosocial stress condition.	None	Not assessed
Zimmermann et al. [87]	Social reward	N = 47 (100 % male) CAN (CUD DSM-IV and abstinent for 28 days): n = 23 (23.86 ± 3.36 yrs) CON (<10 g of lifetime use):	Lifetime: 1503.50 g Monthly: 27.91 ± 4.68 days Duration of use: 77.05 ± 36.56 months Age of	fMRI (whole-brain)	Interpersonal touch paradigm	*Behavior:* ↓ Increase in pleasantness in CAN vs. CON during female vs. male touch. *Brain:* ↓ R dorsal striatum activity in CAN vs. CON during female vs. male touch.	↓ Dorsal striatum during female vs. male touch was positively correlated with lifetime use.	n.s.

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Table 1 (*continued*)

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
		n = 24 (23.67 ± 2.88 yrs)	onset: 15.14 ± 1.27 yrs					

↑: findings indicate increase or improvement; ↓: findings indicate reduction or impairment; ≈: findings indicate no alteration or difference; **ACC**: anterior cingulate cortex; **CAN**: Cannabis group; **CON**: control group; **CUD**: Cannabis use disorder; **DLPFC**: dorsolateral prefrontal cortex; **DSM III**, **IV**: Diagnostic and Statistical Manual of Mental Disorders version 3/4; **fMRI**: functional magnetic resonance imaging; **IFG**: inferior frontal gyrus; **l**: left; **mFG**: medial frontal gyrus; **MFG**: middle frontal gyrus; **MOG**: middle occipital gyrus; **MTG**: middle temporal gyrus; **NAc**: nucleus accumbens; **n.s.**: none significant; **OFC**: orbitofrontal cortex; **PCC**: posterior cingulate cortex; **PET**: positron emission tomography; **PFC**: prefrontal cortex; **PHNO**: Dopamine agonist radiotracer [11C]-(þ)-PHNO; **r**: right; **RCZ**: rostral cingulate zone; **ROI**: region of interest; **SFG**: Superior frontal gyrus; **SPL**: Superior parietal lobule; **STG**: superior temporal gyrus; **ToM**: theory of mind; **TPJ**: temporoparietal junction; **vACC**: ventral anterior cingulate cortex; **Yrs**: years; * study consisted of N=136 participants in total, only results from participants partaking in the fMRI segment of the study were included in this review.

3.2. Social cognition

In addition to Table 1, Fig. 3 provides a summary of evidence from functional magnetic resonance imaging (fMRI) studies comparing neural functioning related to social cognition between cannabis users and controls. Studies pertaining to different subdomains of social cognition are discussed below.

3.2.1. Social influence

Social influence refers to changes in an individual's thoughts, feelings, attitudes, or behaviors resulting from an interaction with another individual or group [57]. Two studies assessed the relationship between cannabis use and social influence using the same experimental paradigm. In Gilman et al. [24,25], users ranging from daily to weekly use and controls participated in a social influence experiment that was designed to measure a participant's likelihood to follow group decisions about the length of a line. Participants were shown two vertical lines, followed by fictitious group decisions indicating which line was longer (influence). This was followed by a choice event, where participants had to decide whether to agree or disagree with the fictitious previous participants' decisions. Gilman et al. [24] focused on neural activation during choice. Region of interest (ROI) analyses of the nucleus accumbens (NAc) revealed a positive correlation between increased NAc activity when making choices that were congruent with the group decision compared to incongruent choices and the number of joints used per week, as well as the number of joints smoked per occasion. Group comparisons revealed increased left frontal pole, left superior frontal gyrus (SFG), and left superior parietal lobule activity in users compared to controls during social influence trials (i.e., trials where a fictitious group decision was shown) compared to trials without social influence (i.e., trials where scrambled graphs or x's were shown instead of fictitious group decisions). The anterior cingulate and insula were activated in both groups when comparing the same conditions, however, users showed increased activation volumes (spatial extent of the activated region) in these areas compared to controls. Gilman et al. [25] focused on neural activation during social influence using a different sample of users. ROI analyses of the caudate revealed increased right caudate activity in users compared to controls. Associations with frequency of use were not analyzed.

3.2.2. Social exclusion

Social exclusion refers to the state of being isolated either physically or mentally from others [83]. Gilman et al. [23] used a cyberball social exclusion task to assess differences in neural functioning in response to social exclusion during virtual ball tossing in users ranging from daily to weekly use and controls. ROI analyses of the ventral anterior cingulate cortex (vACC) revealed that increased vACC activity in users during social exclusion compared to social inclusion was positively correlated with peer conformity and total suggestibility scores (persuadability, physiological suggestibility, physiological reactivity). When comparing

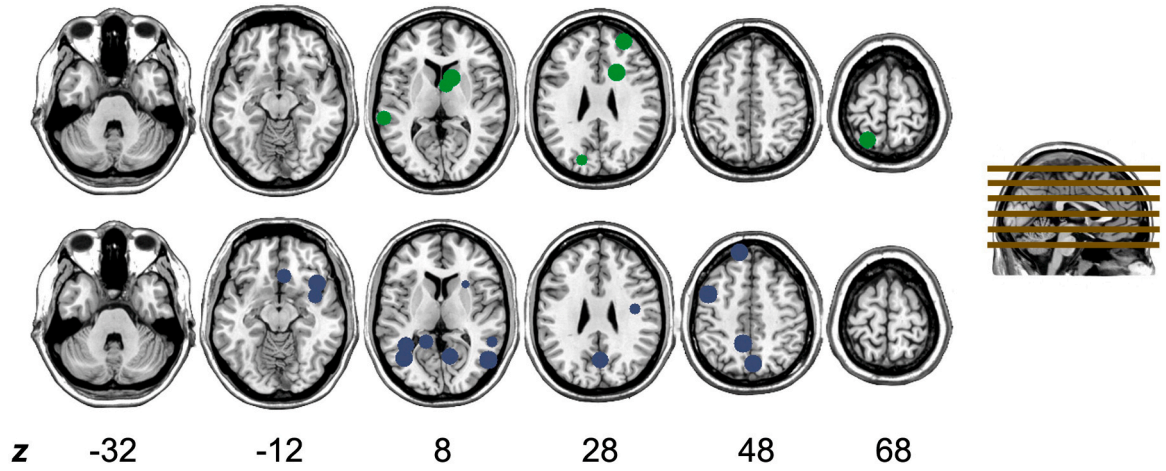

Fig. 3. Evidence from studies comparing social cognition-related neural functioning between cannabis users and controls. **Top row (green)**: areas with evidence supporting increased activity in cannabis users compared to controls. **Bottom row (blue)**: areas with evidence supporting decreased activity in cannabis users compared to controls. Activity masks are 10mm spheres based on peak activity MNI coordinates from significant differences in activity between cannabis users and control participants extracted from the studies. An overview of these coordinates can be found in the supplementary material. **Z**: represents the superior-inferior position in the brain. The spheres are all the same size; however, the vertical position of the horizontal brain section may cause one sphere to appear larger than another.

both groups, users showed decreased activity in the right anterior insula and orbitofrontal cortex (OFC) compared to controls during social exclusion compared to social inclusion. Associations with frequency of use were not analyzed.

3.2.3. Social reward

Social reward encompasses socially rewarding experiences such as being liked, sharing with friends, or participating in celebrations and gatherings [18]. Zimmermann et al. [87] focused specifically on interpersonal touch to study group differences in social reward between male 28-day abstinent dependent (CUD DSM-IV) users and male controls. Compared to controls, users showed a smaller increase in pleasantness during female physical touch compared to male physical touch. Whole-brain analyses revealed decreased right dorsal striatal activity in users compared to controls during female touch compared to male touch. Decreased dorsal striatum activity was positively correlated with lifetime cannabis use.

3.2.4. Psychosocial stress

Psychosocial stress refers to a combination of social and psychological factors leading to feelings of tension, pressure, or strain felt by an individual. Two studies assessed the relationship between cannabis use and psychosocial stress in weekly [45] and dependent (CUD DSM-IV; [86]) users using the Montreal Imaging Stress Task (MIST). Mizrahi et al. [45] used positron emission topography (PET) to study dopamine release during psychosocial stress using the MIST. Findings indicated no significant difference in dopamine displacement between cannabis users and non-using controls during psychosocial stress. Duration of use was significantly correlated with increased PHNO (4-propyl-9-hydroxynaphthoxazine) displacement in the limbic striatum. However, when age was added as a covariate, this correlation was lost. Zhao et al. [86] used fMRI in an all-male sample. ROI analyses of the precuneus found that dependent users showed decreased activity compared to controls during psychosocial stress. This was coupled with a reduction in accuracy, indicating increased susceptibility to psychosocial stress in users compared to controls. Furthermore, stress-task related functional precuneus-SFG connectivity was enhanced in users compared to controls. Associations with heaviness of use were assessed, but none were found to be significant.

3.2.5. Theory of mind

Theory of mind (ToM) can be defined as the ability to explain other people's mental states. This includes but is not limited to the others' beliefs, desires, intentions, and dispositions [21]. Roser et al. [59] investigated differences in neural functioning between male daily to weekly cannabis users and male controls in relation to ToM. The task involved passive viewing of cartoons depicting ToM scenarios (e.g., deception, cooperation) and non-ToM scenarios (pictures shown in scrambled order resulting in meaningless scenarios). When comparing groups, whole-brain analyses revealed that cannabis users exhibited decreased activity in the left parahippocampal gyrus, right precuneus, right cuneus, left SFG, left medial frontal gyrus, left middle frontal gyrus (MFG), superior temporal gyrus (STG), middle temporal gyrus (MTG), and insula compared to controls during ToM scenarios. During the same scenarios, cannabis users displayed increased activity in the left cuneus and right anterior cingulate gyrus compared to controls. Associations with frequency of use were not analyzed.

3.2.6. Empathy

Empathy refers to the ability to understand how others feel (cognitive empathy) as well as to experience emotions felt by others (affective empathy; [75]). [49], studied cognitive and affective empathy in relation to resting state functional connectivity (RSFC) in users with a wide spread of use ranging from weekly to yearly use and a control group. Empathy was measured using the Cognitive and Affective Empathy Test (TECA; [52]). Although users had higher TECA scores on the emotion comprehension scale compared to controls, no associations were found between TECA scores and RSFC. Connectivity analyses showed increased anterior cingulate cortex (ACC)-pre-posterior central gyrus as well as left anterior insula-ACC RSFC in users compared to controls. Associations with frequency of use were not analyzed.

3.3. Emotion recognition

In addition to Table 2, Fig. 4 presents an overview of evidence from fMRI studies comparing neural functioning related to emotion recognition between cannabis users and controls, while Fig. 5 summarizes evidence comparing event-related potential (ERP) components between users and controls in response to affective stimuli. Studies related to different subdomains of emotion recognition are discussed below.

3.3.1. Emotion labelling

3.3.1.1. Emotional scenes. Emotional scenes are referred to as stimuli that depict situations, events, or contexts that evoke strong emotional responses in the observer. Examples of scenes are nature scenes, everyday situations, violence, threats, and erotic content. Scenes are often rated on both valence (positive vs. negative) and arousal (level of emotional activation) by participants. Zimmermann et al. [89], Wesley et al. [82], and Blanco-Hinojo et al. [7] used image-viewing tasks with images from the International Affective Picture system (IAPS; [38]) to study group differences in neural functioning in response to emotional stimuli. Zimmermann et al. [89] compared 28-day abstinent dependent users (CUD DSM-IV) with controls using an almost all-male sample (89.2 %). ROI analyses revealed increased right medial OFC activity in users compared to controls in response to negative stimuli compared to neutral stimuli. Furthermore, connectivity analyses showed increased right medial OFC-left dorsal striatum and increased right medial OFC-left amygdala functional connectivity in users compared to controls in response to negative stimuli versus neutral stimuli. When comparing the same conditions, decreased functional connectivity within the medial OFC was found in users compared to controls. RSFC analyses revealed decreased right medial OFC-left dorsal striatum RSFC in users compared to controls. Associations with heaviness of use were assessed, however, none were found to be significant. Wesley et al. [82] compared daily users with controls. ROI analyses revealed decreased mPFC activity in users compared to controls during the evaluation of stimuli that were judged as emotional. Associations with frequency of use were not analyzed.

Blanco-Hinojo et al. [7] compared RSFC between male daily users and male controls. Measurements were repeated after one month of abstinence. Users rated the images as less arousing compared to controls. Decreased left dorsal caudate-ACC RSFC was negatively correlated with duration of use. Furthermore, increased right ventral putamen-left fusiform gyrus RSFC was positively correlated with urinary cannabinoid levels. Increased caudate nucleus-medial prefrontal cortex (MPFC), posterior cingulate cortex-bilateral angular gyri, and ACC-basal ganglia RSFC in users compared to controls was positively correlated with arousal ratings of emotional scenes. In contrast, increased caudate-sensorimotor cortex and fusiform gyrus-basal ganglia RSFC in users compared to controls was negatively correlated with arousal ratings.

Cassidy et al. [8] and Wölfling et al. [84] compared neural responses to emotional scenes from the IAPS using EEG, focusing specifically on the late positive complex. The late positive complex is generally defined as a positive ERP that peaks at approximately 600 ms after stimulus onset [85]. Cassidy et al. [8] compared male dependent users (CUD DSM-IV) with male controls and found no differences in late positive complex in response to emotional stimuli. Similarly, Wölfling et al. [84] compared dependent users (ICD-10) with controls and also found no significant differences in late positive complex when comparing

Table 2
Characteristics of studies comparing emotion recognition-related neural functioning between cannabis users and controls.

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
Blanco-Hinojo et al. [7]	Emotion labelling (emotional scenes)	N = 57 (100 % male) CAN (>13 uses p/week during last 2 years): n = 28 (21 ± 2 yrs) CON (<15 lifetime use): n = 29 (22 ± 3 yrs)	Lifetime: 5268 ± 4265 joints Yearly: 899 ± 560 joints Duration of use: 6.0 ± 2.5 yrs Age of onset: 14.9 ± 1.0 yrs	fMRI (connectivity seeds: dorsal caudate, dorsal putamen, ventral caudate, ventral putamen)	Rating emotional scenes on valence and arousal	*Behavior:* ↓ Arousal ratings in CAN vs. CON. *Brain:* ↓ Striatum-ACC striatum-mFG, and striatum-fusiform gyrus RSFC in CAN.	↓ L dorsal caudate-ACC RSFC was negatively correlated with duration of use. ↑ R ventral putamen-l fusiform gyrus RSFC was positively correlated with number of cannabinoid metabolites in urine.	↑ Caudate nucleus-mPFC, PCC-bilateral angular gyri, and ACC-basal ganglia RSFC in CAN vs. CON was positively correlated with arousal ratings. ↑ Caudate-sensorimotor cortex and fusiform gyrus-basal ganglia RSFC in CAN vs. CON was negatively correlated with arousal ratings.
Cassidy et al. [8]*	Emotion labelling (emotional scenes)	N = 35 (100 % male) CAN (CUD DSM-IV): n = 20 (25.6 ± 5.5 yrs) CON (no lifetime substance use disorder and no cannabis use in the preceding 3 months): n = 15 (26.1 ± 3.9 yrs)	Past month: 72.8 ± 57 uses (26.4 ± 46 g) Duration of use: 5.7 ± 5.0 yrs	EEG	Rating emotional scenes on valence and arousal	↑ Late positive complex in CAN in pleasant vs. cannabis stimulus conditions.	None	Not assessed
Ehlers et al. [14]	Face discrimination (emotional expression recognition)	N = 314 (45.9 % male) CAN (CUD DSM-III-R): n = 47 (24.66 ± 7 yrs) CAN + other drug dependence (DSM-III-R): n = 66 (30.33 ± 8 yrs) CON (no current substance use disorder): n = 201 (30.46 ± 14 yrs)	Not assessed	EEG	Emotional labelling face discrimination task	*Behavior:* ↑ Response time in female CAN+other drug dependence vs. male or female CON to correctly identified sad faces. *Brain:* ↑ P350 latency in CAN vs. CON in response to sad facial expressions. ↑ P350 latency in female CAN vs. male CAN, male CON, or female CON in response to happy and sad faces. ↑ P450 amplitude in CAN and CAN+other drug dependence vs. CON in response to happy faces. ↑ P450 latency in CAN and CAN+other drug dependence vs. CON in response to neutral faces. ↑ P450 latency in female CAN vs. male CAN in response to sad faces. ↑ P450 latency in	Not assessed	Not assessed

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Table 2 (*continued*)

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
						CAN or CAN+other drug dependence vs. CON in response to sad faces.		
Gruber et al. [28]	Face discrimination (masked emotional expression recognition)	N = 30 (93.3 % male) CAN (>3000 lifetime uses and used in at least 4 of the preceding 7 days): n = 15 (25 ± 8.8 yrs) CON (<6 lifetime uses): n = 15 (26.0 ± 9.0 yrs)	Weekly: 25.6 ± 27.8 joints Age of onset: 14.9 ± 2.5 yrs	fMRI (ROI: amygdala, cingulate gyrus; whole-brain)	Masked facial affect task	↓ Cingulate gyrus, l parietal structures, and r parietal structures in CAN vs. CON in response to masked angry faces. ↓ MACC and amygdala in CAN vs. CON in response to masked angry and happy faces. ↓ STG and l sublobar space in CAN vs. CON in response to masked happy faces. ↑ Lower PCC in CAN vs. CON in response to masked angry and happy faces. ↑ R posterior lobe in CAN vs. CON in response to masked happy faces.	↑ PCC was positively correlated with joints p/week when viewing masked angry faces. ↑ L amygdala was positively associated with joints p/week when viewing masked happy faces. ↑ Midcingulate was positively correlated with urinary cannabinoid levels when viewing masked happy faces.	Not assessed
Heitzeg et al. [31]	Emotion labelling (emotional words)	N = 40 (30 % male) CAN (>100 lifetime uses): n = 20 (19.84 ± 1.45 yrs) CON (<11 lifetime uses): n = 20 (20.51 ± 1.26 yrs)	Lifetime: 618.12 ± 430.41 uses Yearly: 13.4 ± 2.7 uses Age of onset: 13.4 ± 2.7 yrs	fMRI (whole-brain)	Emotion-arousal word task	↓ Amygdala in CAN vs. CON during both negative and positive vs. neutral trials. ↓ R IPL in CAN vs. CON during positive vs. neutral trials. ↓ R MFG, dorsolateral SFG, r MTG, STG, r calcarine fissure, cuneus, lingual gyri, and insula in CAN vs. CON during negative vs. neutral trials. ↑ R DLPFC in CAN vs. CON during positive vs. neutral trials.	Not assessed	↑ Caudal DLPFC during negative vs. neutral trials mediated the relationship between CAN and later negative emotionality and later resiliency. ↑ Cuneus mediated the relationship between CAN and later resiliency.
Ma et al. [41]	Face discrimination (emotional face/shape matching)	N = 46 (71.7 % male) CAN (CUD DSM−5): n = 23 (28.2 ± 3.5 yrs) CON (inclusion criteria unspecified): n = 23 (28.7 ± 3.7 yrs)	Lifetime use: 101–999 uses (n = 5); > 999 uses (n = 18) Age of onset: < 15 yrs (n = 5); 15–17 yrs (n = 10); 18–20 yrs (n = 5); > 20 yrs (n = 2)	fMRI (connectivity seeds: amygdala, fusiform gyrus, hypothalamus, VLPFC, VMPFC)	Emotional face/shape matching task	↑ Effective connectivity modulatory change amygdala-r hypothalamus, amygdala-fusiform gyrus, l VLPFC-l fusiform gyrus in CAN vs. CON in response to angry and fearful faces.	Not assessed	↑ Effective connectivity modulatory change amygdala-r hypothalamus and amygdala-fusiform gyrus in CAN vs. CON in response to angry and fearful faces were positively correlated with perceived stress scale scores.

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Table 2 (*continued*)

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
								↑ Effective connectivity modulatory change l VLPFC-l fusiform gyrus in CAN vs. CON in response to angry and fearful faces was negatively correlated with perceived stress scale scores.
Manza et al. [43]	Face discrimination (emotional face/shape matching)	N = 1206 (45.7 % male) CAN-dependent (CUD DSM-IV): n = 89 (28.6 ± 3.5 yrs) CAN-recreational (>100 lifetime uses but no dependence): n = 87 (28.3 ± 3.9 yrs) CON (<11 lifetime uses): n = 89 (28.6 ± 3.9 yrs) Other (remaining participants in the HCP): n = 941 (28.9 ± 3.7 yrs)	Not assessed	fMRI (whole-brain)	Emotional face/ shape matching task	*Behavior:* ↑ Correlation between cognition and emotion component scores in CAN vs. CON *Brain:* ≈ Activity in CAN vs. CON in emotional faces vs. shapes conditions	Not assessed	↑ Lateral regions, medial frontoparietal regions, anterior insula, caudate in CAN-dependent was positively correlated with scores on cognitive and emotional tasks.
Skosnik et al. [62]	Emotion labelling (emotional words)	N = 26 (%male unspecified; 22.6 ± 4.1 yrs) CAN (>0 p/ week): n = 12 CON (inclusion criteria unspecified): n = 14	Weekly during previous month: 9.2 ± 6.8 joints	EEG	Emotion-arousal word task	↑ P3 amplitude in CAN vs. CON in the oddball and unpleasant trait word conditions.	None	n.s.
Spechler et al. [64]	Face discrimination (emotional expression recognition)	N = 140 (65 % male) CAN (>0 lifetime uses): n = 70 (14.77 ± 0.40 yrs) CON (0 lifetime uses): n = 70 (14.61 ± 0.66 yrs)	Lifetime: 1–2 uses (n = 49); 3–5 uses (n = 7); 6–9 uses (n = 7); 10–19 uses (n = 2); 20–39 uses (n = 3); > 40 uses (n = 3) Age of onset: 13.57 ± 0.94 yrs	fMRI (ROI: amygdala, anterior cingulate, cerebellum, DLPFC, lingual gyrus, MTG, TPJ, VMPFC)	Passive viewing of progressively changing faces	↓ TPJ and DLPFC in CON in response to angry faces vs. neutral faces. ↑ Amygdala in CAN in response to angry faces vs. neutral faces.	↓ TPJ was positively correlated with frequency of use (measure unspecified) in response to both angry and neutral faces.	Not assessed
Sullivan et al. [66]	Face discrimination (emotional inhibitory processing)	N = 66 (53 % male) CAN (>39 uses in the preceding year and >49 lifetime uses): n = 34 (females: 21.4 ± 2.0 yrs; males: 21.7 ± 2.0 yrs) CON (<5 uses in the preceding year and <20 lifetime uses): n = 32 (females: 21.2 ± 2.4 yrs; males: 20.9 ± 2.7 yrs)	Lifetime: 782.5 ± 625.0 uses (female); 1506.5 ± 1666.0 uses (male) Past year: 301.5 ± 245.4 joints (female); 408.0 ± 529.6 joints (male) Monthly during previous 3 months: 74.9 ± 58.7 joints (female);	fMRI (ROI: rACC; whole-brain; connectivity seeds: rACC)	Emotional Go/ No-Go task (emotional inhibitory processing task)	↓ Bilateral rACC in CAN vs. CON during fearful vs. calm no-go trials. ↓ rACC-r cerebellum functional connectivity in female CAN vs. male CAN during successful calm no-go trials.	Not assessed	Not assessed

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Table 2 (*continued*)

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
			95.7 ± 107.1 joints (male) Age of onset: 17.8 ± 1.3 yrs (female); 17.4 ± 1.8 yrs (male)					
Torrence et al. [69]	Face discrimination (emotional attentional bias)	N = 39 (38.5 % male) CAN (>0 uses p/month for at least 1 year): n = 19 (19.84 ± 2.34 yrs) CON (0 lifetime uses): n = 20 (19.5 ± 2.06 yrs)	Monthly: 12.79 ± 17.11 uses Age of onset: 15.84 ± 1.98 yrs	EEG	Dot-probe task	↓ P1 amplitude in CAN vs. CON in response to fearful faces.	↑ N170 amplitude difference in contralateral vs. ipsilateral was positively correlated with uses p/month in response to fearful faces.	Not assessed
Torrence et al. [70]	Face discrimination (masked emotional expression recognition)	N = 36 (38.9 % male; 2.78 % other) CAN (>0 uses p/month for at least 1 year): n = 18 (23.94 ± 4.19 yrs) CON (0 uses in the preceding 2 years): n = 18 (23.56 ± 3.78 yrs)	Monthly: 27.33 ± 31.08 uses Age of onset: 15.88 ± 2.03 yrs	EEG	Masked facial affect task	↓ N170 hemisphere lateralization in CAN vs. CON in response to masked happy, unmasked happy, masked neutral, and unmasked neutral faces. ↑ P1 amplitude in CAN in response to happy faces vs. fearful and neutral faces. ↑ N2 amplitude in CON in response to masked faces vs. unmasked faces.	Not assessed	n.s.
Troup et al. [72]	Face discrimination (implicit and explicit emotional expression recognition)	N = 70 (27.1 % male) CAN (>1 uses p/year): n = 27 (21.3 ± 7.18 yrs) CON (0 lifetime uses): n = 43 (19.3 ± 2.07 yrs)	Frequency (uses): 0–1/month (n = 18); 1–3/month (n = 2); 1–2/week (n = 1); 3–6/week (n = 1); 1/day (n = 2); 2–4/day (n = 3) Years since first use: < 1 yrs (n = 6); 1–2 yrs (n = 8); 2–4 yrs (n = 4); 4–7 yrs (n = 5); 7–10 yrs (n = 1); > 10 yrs (n = 3)	EEG	Implicit and explicit emotional expression recognition and empathy task	↓ P3 amplitude in CAN vs. CON in response to happy, neutral, and fearful faces across explicit, implicit, and empathetic conditions.	None	Not assessed
Troup et al. [73]**	Face discrimination (implicit and explicit emotional expression recognition)	N = 52 (% male unspecified) CAN (inclusion criteria unspecified): n = 32 (age unspecified) CON (inclusion criteria unspecified):	Not assessed	EEG	Implicit and explicit emotional expression recognition and empathy task	↑ P3 amplitude in CAN in response to happy faces vs. fearful faces.	Not assessed	Not assessed

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Table 2 (*continued*)

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
		n = 20 (age unspecified)						
Troup et al. [71]	Face discrimination (implicit and explicit emotional expression recognition)	N = 144 (44.4 % male) CAN-heavy (>0 uses p/week): n = unspecified CAN-casual (<1 uses p/week): n = unspecified CON (inclusion criteria unspecified): n = unspecified	Not assessed	EEG	Implicit and explicit emotional expression recognition and empathy task	↓ P1 amplitude in male CAN-casual vs. male CON in the explicit angry and explicit fear conditions. ↓ P3 amplitude in male CAN-casual vs. CON in the empathy angry condition. ↑ P1 amplitude in male CAN-heavy vs. male CAN-casual in the empathy angry condition. ↑ P1 amplitude in male CON vs. female CON in the explicit neutral, explicit happy, explicit angry, and explicit fear conditions, as well as in the empathy happy and empathy fear conditions. ↑ P1 amplitude in male CAN-casual vs. female CAN-casual in the implicit angry and implicit happy conditions. ↑ P1 amplitude in male CAN-heavy vs. female CAN-heavy in the implicit neutral, implicit angry, implicit happy, and implicit fear condition, as well as in the explicit angry and explicit fear conditions and in the empathy neutral, empathy happy, empathy angry, and empathy fear conditions.	Not assessed	Not assessed
Wallace et al. [79]	Face discrimination (emotional inhibitory processing)	N = 77 (53 % male) CAN (>40 uses in the preceding year): n = 36 (21.6 ± 2.2 yrs) CON (<6 uses in the preceding year and <51 lifetime uses): n = 41 (21.1 ± 2.7 yrs)	Lifetime: 1211.8 ± 1370.6 uses Past year: 425.5 ± 441.8 uses Age of onset (1st time): 15.9 ± 2.2 yrs Age of onset (>1use/week): 17.5 ± 1.7 yrs	fMRI (whole-brain)	Emotional Go/No-Go task (emotional inhibitory processing task)	↑ L cingulate gyrus, l MFG, and l SFG in CAN vs. CON during correct inhibitory responses to calm No-Go trials.	None	Not assessed
Wang et al. [80]	Face discrimination (emotional	N = 132 (28.8 % male) CAN (CUD DSM-IV): n = 66	Not assessed	fMRI (connectivity seeds (cognition network): dACC,	Emotional face/shape matching task	*Behavior:* ↑ Correlation between cognition and emotion	Not assessed	↑ Functional connectivity within the cognition related

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Table 2 (*continued*)

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
	face/shape matching)	(28.03 ± 3.51 yrs) CON (0 lifetime uses): n = 66 (28.23 ± 3.63 yrs)		DLPFC, IOG, IPL, lingual gyrus, MTG. connectivity seeds (emotion network): amygdala, cerebellum, fusiform gyrus, insula, left post central, MFG, precentral gyrus)		component scores in CAN vs. CON *Brain:* ≈ Functional connectivity in emotion VS. cognition related networks in CAN vs. CON.		network was positively correlated with cognition component scores in CON. ↑ Functional connectivity within the cognition related network was negatively correlated with cognition component scores in CAN. ↑ Effective connectivity within the cognition network was negatively correlated with emotion component scores in CAN.
Wesley et al. [82]	Emotion labelling (emotional scenes)	N = 33 (42.4 % male) CAN (>2 uses p/ day for >5 years): n = 17 (25.1 ± 3.1 yrs) CON (inclusion criteria unspecified): n = 16 (27.1 ± 6.3 yrs)	Years of total use: 14.9 ± 2.0 yrs Daily: 4.3 ± 4.4 uses Monthly: 29.3 ± 1.4 uses Age of onset: 14.9 ± 2.0 yrs	fMRI (ROI: ACC, amygdala, IFG, insula, middle cingulate cortex, mPFC, occipital lobe; whole-brain)	Emotion evaluation task	↓ mPFC in CAN during emotional evaluation vs. neutral conditions. ↓ mPFC in CAN vs. CON during emotional evaluation. ↑ Occipital lobe, midbrain, middle cingulate cortex in CAN during emotional evaluation vs. neutral conditions. ↑ R IFG, occipital lobe, middle cingulate cortex and amygdala in CON during emotional evaluation vs. neutral conditions.	Not assessed	Not assessed
Wölfling et al. [84]	Emotion labelling (emotional scenes)	N = 30 (46.7 % male) CAN (>6 uses p/ week): n = 15 (29 ± 6.32 yrs) CON (0 lifetime uses): n = 15 (26.8 ± 3.48 yrs)	Cannabis dependence according to ICD−10 Daily: 2.01 ± 1.20 g during the previous 6 months Duration of use: 9.10 ± 6.33 yrs Age of onset (chronic use): 20.31 ± 4.41 yrs	EEG	Rating emotional scenes on valence and arousal	≈ Late positive complex in CAN vs. CON in response to neutral, negative, and positive stimuli conditions.	Not assessed	n.s.
Zimmermann et al. [88]	Emotion labelling (emotional distancing and reappraisal)	N = 43 (100 % male) CAN (>2 uses p/ week in the preceding year	Lifetime: 1233.22 ± 797.89 uses Weekly: 4.00 ± 3.67 g	fMRI (ROI: amygdala, DLPFC, pre-SMA; connectivity	Emotional distancing and reappraisal task	*Behavior:* ↓ Reappraisal success in CAN vs. CON. *Brain:*	↑ Reappraisal success was negatively correlated with craving.	n.s.

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Table 2 (*continued*)

Author	Subdomain	Sample characteristics and inclusion criteria	Frequency of use	Imaging method	Task	Evidence for group differences	Associations with heaviness of use	Brain-behavior associations
		and >200 lifetime uses): n = 23 (21.24 ± 2.59 yrs) CON (<11 lifetime uses): n = 20 (21.10 ± 3.61 yrs)	Duration of use: 4.28 ± 2.79 yrs Age of onset (1st time): 16 ± 2 yrs	seeds: DLPFC, pre-SMA)		↓ L amygdala-l DLPFC functional connectivity in CAN vs. CON during reappraisal. ↑ Precentral gyrus, r SFG, l mid-cingulate, l precentral gyrus, and r amygdala in CAN vs. CON during reappraisal.		
Zimmermann et al. [89]	Emotion labelling (emotional scenes)	N = 37 (89.2 % male) CAN (CUD DSM-IV and abstinent for 28 days): n = 19 (23.79 ± 3.24 yrs) CON (<10 g of lifetime use): n = 18 (24.11 ± 3.14 yrs)	Not assessed	fMRI (ROI: amygdala, anterior insula, cingulate, hippocampus OFC, striatum; whole-brain; connectivity seeds: amygdala, anterior insula, cingulate, hippocampus OFC, striatum)	Rating emotional scenes on valence and arousal	↓ R mOFC-l dorsal striatum RSFC in CAN vs. CON. ↓ mOFC-mOFC functional connectivity in CAN vs. CON in response to negative vs. neutral stimuli. ↑ R mOFC in CAN vs. CON in response to negative vs. neutral stimuli. ↑ R mOFC-l dorsal striatum and l amygdala functional connectivity in CAN vs. CON in response to negative vs. neutral stimuli.	None	Not assessed

↑: findings indicate increase or improvement; ↓: findings indicate reduction or impairment; ≈: findings indicate no alteration or difference; **ACC**: anterior cingulate cortex; **CAN**: Cannabis group; **CON**: control group; **CUD**: Cannabis use disorder; **dACC**: dorsolateral anterior cingulate cortex; **DLPFC**: dorsolateral prefrontal cortex; **DSM III**, **IV**, **5**: Diagnostic and Statistical Manual of Mental Disorders version 3/4/5; **EEG**: electroencephalography; **fMRI**: functional magnetic resonance imaging; **HCP**: Human connectome project; **ICD-10**: International Classification of Diseases and Related Health Problems version 10; **IFG**: inferior frontal gyrus; **IOG**: inferior occipital gyrus; **IPL**: Inferior parietal lobe; **l**: left; **MACC**: midanterior cingulate cortex; **mFG**: medial frontal gyrus; **MFG**: middle frontal gyrus; **mOFC**: medial orbitofrontal cortex; **mPFC**: medial prefrontal cortex; **MTG**: middle temporal gyrus; **n.s.**: none significant; **OFC**: orbitofrontal cortex; **PCC**: posterior cingulate cortex; **r**: right; **rACC**: rostral anterior cingulate cortex; **ROI**: region of interest; **RSFC**: resting state functional connectivity; **SFG**: Superior frontal gyrus; **SMA**: supplementary motor area; **STG**: superior temporal gyrus; **TPJ**: temporoparietal junction; **VLPFC**: ventrolateral prefrontal gyrus; **VMPFC**: ventromedial prefrontal cortex; **Yrs**: years; * study consisted of N=70 participants in total, schizophrenic patient users and schizophrenic patient non-users results were excluded from this review; ** study consisted of N=122 participants in total, depressed patient users and depressed patient non-users results were excluded from this review.

emotional stimulus conditions. Associations with frequency of use were not analyzed in both studies.

3.3.1.2. Emotional words. Heitzeg et al. [31] and Skosnik et al. [62] used an emotion-arousal word task during which participants were presented with either pleasant words (e.g. hope, bright, love), unpleasant words (e.g. war, doom, corpse), or neutral words (e.g. table, lawn, "x", "o"). Heitzeg et al. [31] compared neural functioning between monthly users and controls. Whole-brain analyses showed decreased amygdala activity in users compared to controls during both positive and negative word trials compared to neutral word trials. The comparison of positive and neutral word trials revealed decreased activity in the right inferior parietal lobe and increased activity in the right dorsolateral prefrontal cortex (DLPFC) in users compared to controls. Furthermore, decreased right MFG, dorsolateral SFG, right MTG, STG, right calcarine fissure, cuneus, lingual gyri, and insula activity in users compared to controls during negative word trials compared to neutral word trials. Increased caudal DLPFC activity during negative word trials compared to neutral word trials mediated the relationship between the cannabis group and future negative emotionality as well as future resiliency. Moreover, increased cuneus activity mediated the relationship between cannabis group and future resiliency. Here, resiliency is defined as the capacity to adapt one's behavior in response to the demands of the (social) environment [16], a construct that has generally been associated with emotion regulation [15]. Associations with frequency of use were not analyzed. Skosnik et al. [62] compared weekly users with controls using EEG and found an increased P3 amplitude – an ERP commonly associated with stimulus evaluation [77] – in users compared to controls in neutral (oddball) and unpleasant word conditions. Associations with heaviness of use were assessed, but none were found to be significant.

3.3.1.3. Emotional distancing and reappraisal. Emotional distancing is referred to as mentally separating oneself from a situation or emotional experience [54]. Reappraisal is described as a cognitive strategy where an individual reinterprets the meaning or emotion of a situation to

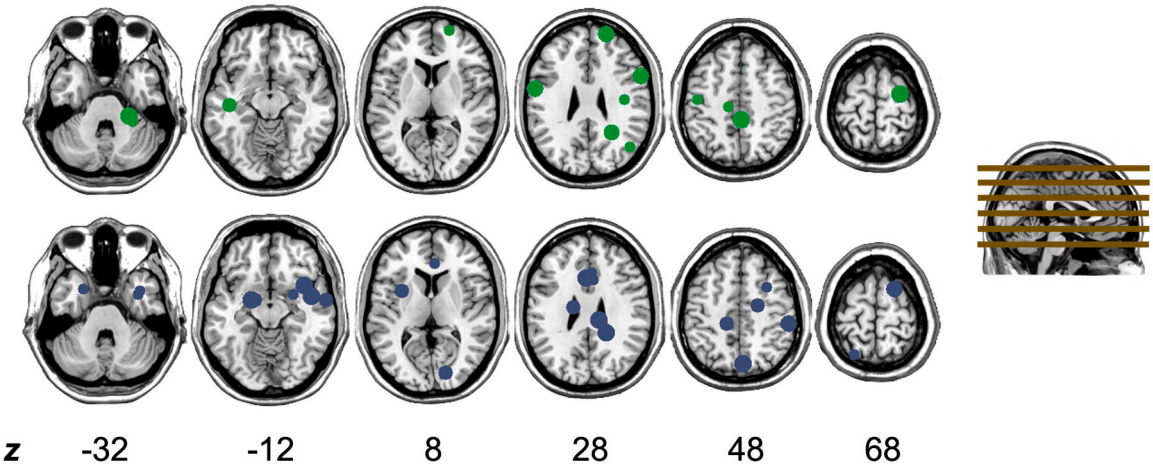

Fig. 4. Evidence from studies comparing emotion recognition-related neural functioning between cannabis users and controls in response to affective stimuli. **Top row (green)**: areas with evidence supporting increased activity in cannabis users compared to controls. **Bottom row (blue)**: areas with evidence supporting decreased activity in cannabis users compared to controls. Activity masks are 10mm spheres based on peak activity MNI coordinates from significant differences in activity between cannabis users and control participants extracted from the studies. An overview of these coordinates can be found in the supplementary material. **Z**: represents the superior-inferior position in the brain. The spheres are all the same size; however, the vertical position of the horizontal brain section may cause one sphere to appear larger than another.

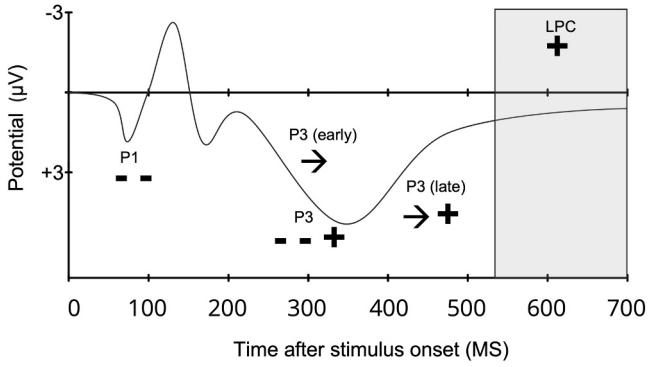

Fig. 5. Evidence from studies comparing emotion recognition-related event-related potentials between cannabis users and controls in response to affective stimuli. **(-)**: study that found evidence for a decrease in amplitude; **(+)**: study that found evidence for an increase in amplitude; **(→)**: study that found evidence for increased latency; **LPC**: late positive component; **P**: positive waveform deflection.

change their emotional response. In Zimmermann et al. [88], both constructs were studied in 28-day abstinent dependent (CUD DSM-IV) users and controls. Stimuli were extracted from the IAPS. Users overall showed significantly lower reappraisal success compared to controls. ROI analyses demonstrated increased activity in the precentral gyrus, right SFG, left mid-cingulate, left precentral gyrus, and right amygdala in users compared to controls during emotional distancing. Connectivity analyses revealed decreased left amygdala-left DLPFC functional connectivity in users compared to controls, also during emotional distancing. Reappraisal success was negatively correlated with craving.

3.3.2. *Face discrimination*

3.3.2.1. Emotional expression recognition. Emotional expression recognition is referred to as the ability to accurately perceive and understand emotions expressed by others through facial expressions [34]. Ehlers et al. [14] compared ERPs in response to emotional faces between dependent users (CUD DSM-III-R), dependent users with a drug dependence in addition to CUD, and controls. Female dependent users with an additional drug dependence responded significantly slower to correctly identified sad faces compared to controls (male and female). Increased P350 latency was found in dependent users compared to controls in response to sad facial expressions. Further focusing on sex differences and the P350, increased P350 latency was also found when comparing female dependent users with male dependent users and both female and male controls in response to both happy and sad faces. Looking at the P450, increased P450 amplitude was found in dependent users as well as dependent users with an additional dependency compared to controls in response to happy facial expressions. Dependent users and dependent users with an additional dependency also showed increased P450 latency compared to controls in response to neutral facial expressions. Focusing on sex differences and the P450, increased P450 latency was also found in female dependent users compared to male dependent users in response to sad facial expressions. The same effect was found when comparing dependent users and dependent users with an additional drug dependence with controls. Associations with frequency of use were not analyzed.

Spechler et al. [64] compared neural functioning between lifetime users (>1 lifetime uses) and controls. Participants passively viewed video clips of progressively changing faces or control images. ROI analyses revealed no group differences in neural functioning between users and controls. However, decreased temporoparietal junction activity in response to both neutral and negative faces was positively correlated with frequency of use (measure unspecified).

3.3.2.2. Implicit vs. explicit emotional expression recognition. Explicit emotional expression recognition is referred to as a process that requires conscious and intentional language-based processing of emotional cues [58,72]. Implicit emotional expression recognition is characterized by a process that operates at a subconscious level and involves automatic responses to non-verbal cues [58,72]. Troup et al. [72,73,] investigated differences in explicit and implicit emotional expression recognition using EEG. In their experiments, participants were shown images of faces after which either the sex of the face (implicit), the emotion portrayed by the face (explicit), or ability to empathize with the face (empathy) needed to be reported. Troup et al. [72] compared users ranging from daily to monthly use with controls. A decrease in P3 amplitude was found in users compared to controls in response to happy, neutral, and fearful face types, but not to angry face types, across explicit, implicit, and empathetic conditions. Troup et al. [73] compared a cannabis group with an unspecified frequency of use with controls and

measured an increase in P3 amplitude in response to happy facial expressions compared to fearful facial expressions (task condition not mentioned).

Troup et al. [71] focused specifically on sex differences using EEG. Participants were either classified as heavy user (>1 uses p/week), casual user (0–1 uses p/week), or control (unspecified). Results revealed increased P1 – an ERP commonly associated with early visual processing [76] – amplitude in male casual users compared to female casual users during the implicit angry and happy conditions. Within the heavy user group, increased P1 amplitude was also found when comparing male and female heavy users in response to the implicit neutral, implicit angry, implicit happy, and implicit fear conditions, as well as in the explicit angry and explicit fear conditions and in the empathy neutral, empathy happy, empathy angry, and empathy fear conditions. Within the control group increased P1 amplitude was further found in males compared to females in the explicit neutral, explicit happy, explicit angry, and explicit fear conditions, as well as in the empathy happy and empathy fear conditions. When comparing male casual users with male controls, decreased P1 amplitude was found in the explicit angry and explicit fear conditions. Further between-group comparisons revealed increased P1 amplitude in male heavy users compared to male casual users in the empathy angry condition as well as decreased P3 amplitude in male casual users compared to controls in the empathy angry condition. None of the studies in this section analyzed associations with frequency of use.

3.3.2.3. Masked emotional expression recognition. Masked emotional expression recognition refers to a process of rapid (<40 ms) emotional expression recognition that does not reach the level of conscious awareness. Gruber et al. [28] and Torrence et al. [70] used masked emotional awareness tasks to restrict explicit emotional awareness of facial expressions. Gruber et al. [28] included users with at least 3000 lifetime uses as well as having used in at least 4 of the preceding 7 days and controls. Whole-brain analyses revealed decreased activity in the STG and left sublobar space as well as increased activity in the right posterior lobe in users compared to controls in response to masked happy faces. In response to masked angry faces, decreased activity was found in the cingulate gyrus and parietal cortex in users compared to controls. ROI analyses showed decreased activity in the mid-ACC and amygdala as well as increased posterior cingulate cortex (PCC) activity in users compared to controls in response to masked angry and masked happy faces. Increased PCC activity in response to masked angry faces was positively correlated with the number of joints used per week. Increased left amygdala activity in response to masked happy faces was positively associated with the number of joints used per week. Furthermore, increased midcingulate activity in response to masked happy faces was positively correlated with urinary cannabinoid levels.

Torrence et al. [70] included daily, almost daily, and monthly users as well as controls. Using EEG, reduced N170 – an ERP commonly associated with the neural processing of faces [61,65] – hemisphere lateralization was found in users compared to controls in response to masked happy, unmasked happy, masked neutral, and unmasked neutral faces. Associations with frequency of use were not analyzed.

3.3.2.4. Emotional face matching. Ma et al. [41], Manza et al. [43], and Wang et al. [80] conducted experiments where participants matched a face on top of the screen to one of two faces at the bottom. The same setup with shapes was used as a control condition. Ma et al. [41] included users with a CUD (CUD DSM-V) as well as a control group and used dynamic causal modeling to assess directional interactions between brain regions. Results revealed an increase in amygdala-right hypothalamus, amygdala-fusiform gyrus, and left ventrolateral prefrontal cortex (VLPFC)-left fusiform gyrus effective connectivity modulatory change (EC) in users compared to controls in response to angry and fearful faces. Increased amygdala-right hypothalamus and amygdala-fusiform gyrus EC were positively correlated with Perceived Stress Scale scores. In contrast, increased left VLPFC-left fusiform gyrus EC was negatively correlated with Perceived Stress Scale scores.

Manza et al. [43] included dependent users (CUD DSM-IV), recreational users (>100 lifetime uses but no CUD), and controls. Exploratory whole-brain analyses found no differences in neural functioning when comparing emotional face and shape conditions between users and controls. However, increased activity in the lateral regions, medial frontoparietal regions, anterior insula, and caudate in dependent users was positively correlated with scores on cognitive and emotional tasks. Furthermore, users showed an increased correlation between cognition (e.g., scores on a working memory task) and emotion (e.g., emotional face matching) component scores compared to controls. Wang et al. [80] further built upon Manza et al. [43] by analyzing functional and effective connectivity in relation to cognitive and emotional component scores. No differences in functional connectivity were found between dependent users and controls. Increased functional connectivity within a cognition related network (IPL, DLPFC, dACC, IOG, lingual gyrus, MTG) was negatively correlated with cognition component scores in users. The opposite effect was found in controls. Furthermore, effective connectivity within this cognition network was negatively correlated with emotion component scores in users only. Similar to Manza et al. [43], users, compared to controls, showed an increased correlation between cognition and emotion component scores. None of the studies in this section analyzed associations with frequency of use.

3.3.2.5. Emotional attentional bias. Emotional attentional bias in the context of this section, refers to a tendency to focus on threat-related stimuli. Torrence et al. [69] investigated attentional bias towards fearful faces using a dot-probe task in users ranging from monthly to daily cannabis use and controls using EEG. Users showed a decreased P1 amplitude compared to controls in response to fearful faces. Furthermore, an increased N170 amplitude difference between contralateral and ipsilateral electrodes in response to fearful faces was positively correlated with uses per month.

3.3.2.6. Emotional inhibitory processing. Response inhibition is referred to when describing someone's ability to suppress automatic responses during a task [48]. Wallace et al. [79] and Sullivan et al. [66] used an emotional go/no-go task to study emotional inhibitory processing in users ranging from daily to monthly use as well as controls. Participants were instructed to press a button for a specific emotional face and to withhold from pressing when presented with a different type of face. Participants in Wallace et al. [79], were only included after two weeks of abstinence of cannabis use. Whole-brain analyses revealed increased left cingulate gyrus, left MFG, and left SFG activity in users compared to controls during correctly inhibited calm face type no-go trials. Heaviness of use was unrelated to task-related activity. A ROI analysis of the rostral ACC in Sullivan et al. [66] found decreased rACC activity in users compared to controls during fearful vs. calm face type no-go trials. Connectivity analyses revealed decreased rACC-right cerebellum functional connectivity when comparing female users with male users during correctly inhibited calm face type no-go trials. Associations with frequency of use were not analyzed.

4. Discussion

This systematic review assessed the evidence regarding the associations of long-term cannabis use with social cognition, emotion recognition, and neural functioning. Examining these associations is of particular importance as social factors have demonstrated to play a significant role in both the initiation of cannabis use and the development of cannabis use disorder [55,56,78]. We presented a comprehensive overview of the current evidence about how cannabis use is associated with various processes, including social influence, social

exclusion, social reward, psychosocial stress, ToM, empathy, and emotion recognition, as well as the potential underlying brain mechanisms. The evaluated studies suggest wide-spread differences in brain functionality during social cognition and emotion recognition tasks between long-term cannabis users and controls. However, heterogeneity in the severity of cannabis use and employed designs is large, and replications are sparse. Moreover, studies investigating individuals with CUD specifically, associations with cannabis use severity, and gender differences are largely missing. A comprehensive evaluation of the most consistent findings is discussed below, along with significant knowledge gaps and potential directions for future research.

4.1. Social cognition

Evidence suggests that cannabis users show differences in various subdomains of social cognition, along with concurrent differences in activity within the associated brain regions compared to controls (Fig. 3; Table 1). Notably, these differences were observed in areas associated with social influence, social exclusion, psychosocial stress, and social reward where some of the findings can be described as contradicting. To illustrate, studies indicate that cannabis users may be more vulnerable to social influence [24,25] and to psychosocial stress [86]. Contrastingly, cannabis users have demonstrated lower responsiveness to social rejection as well as social rewards [23,87]. Overall, the differences observed between users and controls seem to be dependent on the social context. Users may be more vulnerable to social influence and psychosocial stress but at the same time display decreased emotional sensitivity or emotional numbing in response to social rewards and social exclusion possibly as a coping mechanism. As such, trying to leverage positive social influence by for example using peer group-based approaches might provide clinical benefit [13,63,68]. However, these effects could be driven by task load. For instance, it seems that during more demanding social situations (e.g., mental arithmetic task during the MIST, evaluating stimuli under time pressure; [24,25,86]) the influence of social factors appears to be stronger in users compared to controls. Conversely, in less demanding social situations (e.g., simple ball toss, interpersonal touch; [23,87] the influence of social factors seems to have an opposite effect in users compared to controls. It might be that users are more vulnerable in more socially demanding situations compared to less socially demanding situations, regardless of the specific social cognitive subdomain involved in the interaction. This aligns with findings from a recent study on working memory and cannabis use, which reported significantly lower working memory activation in users compared to controls, but only during the most challenging trials of the working memory task [35]. Evidence regarding ToM and empathy did not yield definitive or consistent findings regarding the direction of their effects. In the context of ToM, cannabis users showed both higher and lower brain activity across various regions compared to controls [59]. This suggests that prolonged cannabis use co-occurs with mixed brain responses related to ToM. Regarding empathy, despite users achieving higher scores on the TECA for empathy, as well as higher RSFC within the empathy core network [81] in users compared to controls, the absence of correlations between behavioral and brain measures advises caution against drawing strong conclusions [49].

4.2. Emotion recognition

The evidence on the association between cannabis use and emotion recognition, as well as functioning of the commonly associated brain regions, remains inconsistent and largely aligns with the conclusions of MacKenzie and Cservenka's [42] narrative review on cannabis use and emotion processing. EEG studies investigating early event-related potentials found a reduced P1 amplitude in cannabis users in response to negative affective stimuli (Fig. 5), compared to controls ([69] & [71]). This could indicate that cannabis users have a lower attentional bias towards faces displaying negative emotions [69]. Current research does not provide conclusive evidence about the N170 face processing component [69,70]. Studies examining later potentials also show a lack of coherence, with results heavily influenced by the specific tasks used and the emotions compared between users and controls [8,84]. Additionally, there is considerable variation in which components are analyzed and the terminology employed to describe them. For instance, even studies focusing on the same component, like the P3, show significant discrepancies in the time windows used for detection, ranging from 200 to 400ms [72] to 300–900ms [62].

fMRI studies indicate that cannabis users typically exhibit altered responses to affective stimuli in the amygdala, frontal cortex, and cingulate cortex (Fig. 4; Table 2). Some studies observed higher amygdala activity in users compared to controls [64,82], whereas other studies reported lower activity in users compared to controls in response to affective stimuli [28,31]. This finding adds to the inconsistent patterns of amygdala activation reported in neuroimaging studies of substance use, indicating that this variability is not limited specifically to cannabis use [30]. Variations in use severity and tetrahydrocannabinol (THC) and cannabidiol (CBD) ratios in cannabis may account for inconsistencies in amygdala findings. Rossi et al. [60] for example reported that higher THC doses (>10 mg) led to heightened amygdala activation in response to aversive stimuli, whereas lower doses produced the opposite effect, as indicated in their systematic review [19,20,26,5,51,6]. Whereas CBD may attenuate amygdala activation in response to aversive stimuli [20,6]. While these findings primarily pertain to the acute effects of cannabis, it remains speculative whether these effects could persist long-term. Additionally, a recent study by Taubert et al. [67] found that the amygdala exhibits varying responses based on stimulus characteristics, showing greater activation to inanimate objects and animals compared to faces, bodies, and social stimuli. This finding, combined with significant methodological variations observed across studies, could contribute to explaining the inconsistent findings regarding amygdala activity.

Regarding the cingulate cortex, the more anterior segments within the cingulate cortex showed decreased activation towards affective stimuli, while the more posterior segments showed increased activation in the same condition [28,66]. Similar results were found in a study that solely focused on associations with intensity of use by Leiker et al. [39] where CUD symptom severity was negatively associated with activity in the ACC. The findings of increased ACC activation during correctly inhibited calm no-go trials from Wallace et al. [79] could be more related to inhibition during the go/no-go task rather than the emotionality of the stimulus, as response inhibition has previously been associated with increased cingulate cortex activity in cannabis users [27,32].

Regarding frontal areas, results varied depending on specific frontal segments, emotionality of stimuli, and tasks involved. To illustrate, in users compared to controls, increased medial orbitofrontal activity was found in response to negative compared to neutral affective stimuli [89], decreased MPFC activity in response to stimuli that were judged as emotional (regardless of valance; [82]), increased SFG activation during emotional reappraisal [88], and increased DLPFC activity in response to positive affective stimuli compared to neutral affective stimuli [31]. There is substantial evidence that chronic cannabis use has been associated with changes in neural functioning across the frontal cortex [11,44]. However, the nature of this association with emotion recognition remains unclear and requires further research.

4.3. Limitations

While the present review is the first to systematically review studies encompassing social cognition, emotion recognition, cannabis use, and neuroimaging, there are several important limitations of the included studies that should be considered. First, the sample of studies in the social cognition domain was relatively small (n = 8) and contained only one or two studies per subdomain. Moreover, some social cognitive

constructs are currently absent in this review because of a lack of conducted studies. These include social decision-making [55], moral decision-making [47], and social attunement [36,37]. Secondly, although the sample of studies on emotion recognition was larger (n = 21), heterogeneity of cannabis use severity and implemented tasks across studies complicated the comparison of results between studies. Furthermore, some studies did not report sample characteristics, which complicates integration of the reported findings [14,43,62,71,73,80]. Additionally, there is significant overlap in the co-use of alcohol or other drugs across nearly all reviewed studies, samples are frequently small, and consist exclusively of male participants. The inclusion of exclusively male participants highlights potential limitations given the consistent gender differences observed in emotion recognition [59,7,8,86–88]. In addition, analyses exploring associations with heaviness of use are largely absent. Due to the absence of longitudinal studies with measurements before the onset of use, it remains unclear whether the differences in neural functioning discussed in this review are caused by cannabis use or pre-existing differences that contributed to the onset of cannabis use. Moreover, it is important to highlight that there are significant variations in the methods used to measure cannabis exposure across studies. This underscores the need for a standardized approach for assessing cannabis exposure. Ideally, this would involve combining self-report measures with biomarkers, such as urinary cannabis levels, while acknowledging that urinary cannabis levels can be influenced by factors such as body weight or sex, which may introduce additional variability into the analysis [10,40]. Despite these limitations, we believe that the present systematic review provides an important starting point for future studies, highlighting significant research gaps and opportunities for new hypotheses.

4.4. Concluding remarks

Studies found significant differences in neural functioning across multiple domains. The primary findings across social cognitive subdomains align with Gilman [22], showing increased activity during social influence, as well as decreased sensitivity to social exclusion. The present review further expands on this by presenting evidence for decreased neural responding in cannabis users versus controls in the context of social reward processing and psychosocial stress. Evidence regarding ToM and empathy remains inconclusive. Additionally, findings on emotion recognition also remain inconclusive and appear to be significantly influenced by factors such as gender, type of stimulus, and heaviness of use. Overall, the functional implications, the causal relationship with use, and the role of individual user characteristics, including the severity of CUD symptoms and gender, remain unclear. Identifying deficits in social cognition and emotion recognition, along with their neural substrates, could be useful for developing targeted intervention strategies and prevention measures. Given the importance of social processes in both the onset and development of CUD, further research is necessary with larger samples and samples specifically consisting of individuals with CUD.

CRediT authorship contribution statement

Karis Colyer-Patel: Writing – review & editing, Methodology. **Mika Mautner-Rohde:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **Janna Cousijn:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Helle Larsen:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Christophe Romein:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to correct grammar. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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Appendix A

Table 3
Search syntax from Web of Science, last accessed on August 8, 2024

Web of Science Core Collection (Arts & Humanities Citation Index (A&HCI) - 1975-present, Conference Proceedings Citation Index - Science (CPCI-S) - 1990-present, Conference Proceedings Citation Index - Social Science & Humanities (CPCI-SSH) - 1990-present, Science Citation Index Expanded (SCI-EXPANDED) - 1975-present, Social Sciences Citation Index (SSCI) - 1975-present, Essential Sources Citation Index (ESCI) - 2005-present)
#1 Cannabis
TS = (“marijuana” OR “marijuana abuse” OR “marihuana” OR “marijuana smoking” OR “dronabinol” OR “cannabi*” OR “tetrahydrocannabin*” OR “CUD” OR “THC”)
#2 Social cognition & emotion recognition
TS = (“social cognition” OR “social influence” OR “peer influence” OR “peer information” OR “peer” OR “friend*” OR “antisocial” OR “social perception” OR “social processing” OR “social decision making” OR “social functioning” OR “social learning” OR “social exclusion” OR “psychosocial” OR “psychosocial stress” OR “peer groups” OR “social rejection” OR “social interaction” OR “social decision making” OR “social reward” OR “social threat” OR “social network” OR “fear processing” OR “affect recognition” OR “emotion*” OR “face perception” OR “facial expressions” OR “empathy” OR “theory of mind”)
#3 Neuroimaging

(*continued on next page*)

Table 3 (*continued*)

TS = (“fMRI” OR “MRI” OR “functional magnetic resonance imaging” OR “functional magnetic imaging” OR “diffusion tensor imaging” OR “brain activity” OR “brain structure” OR “brain anatomy” OR “brain connectivity” OR “resting state” OR “resting state functional connectivity” OR “rsfc” OR “functional imaging” OR “brain activity patterns” OR “insula” OR “striatum” OR “NAc” OR “nucleus accumbens” OR “EEG” OR “electroencephalography” OR “ERP” OR “event-related potential” OR “electrophysiology” OR “encephalography” OR “MEG” OR “magnetoencephalography” OR “neuro*” OR “PET” OR “positron emission tomography” OR CT OR “computed tomography scan” OR “fNIRS”)
#1 AND #2 AND #3

Table 4
Search syntax from PsycINFO, last accessed on August 8, 2024

PsycINFO (Ovid, APA PsycInfo)
#1 Cannabis
(Cannabis/ OR "cannabis use disorder"/ OR "cannabis use"/ OR cannabinoids/ OR marijuana/ OR tetrahydrocannabinol/ OR dronabinol OR (cannabi* OR marijuana OR marihuana OR tetrahydrocannabin* OR CUD OR THC OR dronabinol).ti,ab,id.)
#2 Social cognition & emotion recognition
("social cognition"/ OR "social behavior"/ OR "facial affect recognition"/ OR "interpersonal interaction"/ OR "social interaction"/ OR "social motivation"/ OR "social neuroscience"/ OR "social perception"/ OR "prosocial behavior"/ OR "antisocial behavior"/ OR "social acceptance"/ OR "social adjustment"/ OR "social approval"/ OR "social reinforcement"/ OR "social emotional learning"/ OR "social acceptance"/ OR "peer relations"/ OR "psychosocial factors"/ OR "social stress"/ OR "psychosocial stress"/ OR "social influences"/ OR "interpersonal influences"/ OR "emotion recognition"/ OR "emotional cognition"/ OR "face perception"/ OR "facial expressions"/ OR "social emotional learning"/ OR "emotions"/ OR "emotional intelligence"/ OR "fear processing" OR "theory of mind"/ OR "empathy"/ OR ("socia*" OR "peer*" OR "friend*" OR "emotion*" OR "affective*" OR "theory of mind").ti,ab,id.)
#3 Neuroimaging
("MRI"/ OR "magnetic resonance imaging"/ OR "neuroimaging"/ OR "tomography"/ OR "diffusion tensor imaging"/ OR "functional magnetic resonance imaging"/ OR "CAT Scan"/ OR "positron emission tomography"/ OR "PET imaging"/ OR "PET scan"/ OR "magnetoencephalography"/ OR "electroencephalography"/ OR "EEG"/ OR "event related potentials"/ OR "electrophysiology"/ OR MEG OR "brain connectivity"/ OR ("fMRI" OR "MRI" OR "PET" OR "EEG" OR "MEG" OR "CT" OR "neura*" OR "brain*" OR "tomography" OR "fNIRS").ti,ab,id.)
#1 AND #2 AND #3

Table 5
Search syntax from Medline, last accessed on August 8, 2024

Medline (Ovid MEDLINE ALL, which includes Epub Ahead of Print, In-Process, In-Data-Review & Other Non-Indexed Citations and Daily, 2023–24)
#1 Cannabis
(cannabis/ OR dronabinol/ OR marijuana abuse/ OR cannabinoids/ OR marijuana smoking/ OR (cannabi* OR marijuana OR marihuana OR tetrahydrocannabin* OR CUD OR THC OR dronabinol).ti,ab,kf)
#2 Social cognition & emotion recognition
(social cognition/ OR social perception/ OR theory of mind/ OR interpersonal relations/ OR social behavior/ OR social adjustment/ OR social adjustment/ OR social inclusion/ OR social isolation/ OR social skills/ OR social interaction/ OR social integration/ OR social environment/ OR peer group/ OR social learning/ OR psychosocial functioning/ OR facial recognition/ OR facial expression/ OR emotional intelligence/ OR fear processing OR empathy/ OR (socia* OR peer* OR friend* OR emotion* OR affective* OR theory of mind).ti,ab,kf)
#3 Neuroimaging
(magnetic resonance imaging/ OR diffusion magnetic resonance Imaging/ OR neuroimaging/ OR functional neuroimaging/ OR diffusion tensor imaging/ OR brain mapping/ OR positron-emission tomography/ OR tomography/ OR electroencephalography/ OR brain waves/ OR magnetoencephalography/ OR brain/ OR evoked potentials/ OR (fMRI OR MRI OR PET OR EEG OR MEG OR CT OR neura* OR brain* OR tomography OR fNIRS).ti,ab,kf)
#1 AND #2 AND #3

Table 6
Search syntax from Embase, last accessed on August 8, 2024

Embase (Elsevier)
#1 Cannabis
(“cannabis”/de OR “cannabis smoking”/de OR “cannabis use”/de OR “cannabinoid”/de OR “cannabis addiction”/de OR “marijuana”/de OR “cannabis use disorder”/de OR “dronabinol”/de OR “tetrahydrocannabinol”/de OR (cannabi* OR marijuana OR marihuana OR tetrahydrocannabin* OR CUD OR THC OR dronabinol):ti,ab,kw)
#2 Social cognition & emotion recognition
(“social cognition”/de OR “social behavior”/de OR “social reward”/de OR “peer pressure”/de OR “peer group”/de OR “social decision making”/de OR “social interaction”/de OR “social learning”/de OR “social exclusion”/de OR “social rejection”/de OR “social inclusion”/de OR “psychosocial”/de OR “emotion recognition”/de OR “emotion assessment”/de OR “emotion perception”/de OR “emotional intelligence”/de OR “empathy”/de OR “theory of mind”/de OR “facial

(*continued on next page*)

Table 6 (*continued*)

recognition"/de OR "fear processing" OR ("socia*" OR peer* OR friend* OR emotion* OR affective* OR "theory of mind"):ti,ab,kw)
#3 Neuroimaging
("functional magnetic resonance imaging"/de OR "functional neuroimaging"/de OR "brain tomography"/de OR "MRI"/de OR "fMRI"/de OR "brain structure"/de OR "electroencephalogram"/de OR "resting state network"/de OR "diffusion tensor imaging"/de OR "electroencephalograph"/de OR "EEG"/de OR "magnetoencephalography system"/de OR "MEG"/de OR "positron emission tomography"/de OR "PET"/de OR "x-ray computed tomography"/de OR "tomography"/de OR (fMRI OR MRI OR PET OR EEG OR MEG OR CT OR neura* OR brain* OR tomography OR fNIRS):ti,ab,kw)
#1 AND #2 AND #3

Table 7
Search syntax from Cochrane, last accessed on August 8, 2024

Cochrane
#1 Cannabis
("marijuana abuse" OR "marijuana smoking" OR cannabi* OR marijuana OR marihuana OR tetrahydrocannabin* OR CUD OR THC OR dronabinol):ti,ab,kw
#2 Social cognition & emotion recognition
("psychosocial functioning" OR "psychosocial deprivation" OR "psychosocial support systems" OR "facial recognition" OR "facial expression" OR "affect recognition" OR "theory of mind" OR empathy OR "fear processing" OR socia* OR peer* OR friend* OR emotion* OR affective* OR "theory of mind"):ti,ab,kw
#3 Neuroimaging
("magnetic resonance imaging" OR "neuroimaging" OR "brain mapping" OR "brain" OR "brain waves" OR "diffusion tensor imaging" OR electroencephalography OR "evoked potentials" OR "electroencephalography phase synchronization" OR Magnetoencephalography OR "positron-emission tomography" OR "four-dimensional computed tomography" OR fMRI OR MRI OR PET OR EEG OR MEG OR CT OR neura* OR brain* OR tomography OR fNIRS):ti,ab,kw
#1 AND #2 AND #3

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bbr.2025.115755.

Data availability

No data was used for the research described in the article.

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