Chapter 3

The Role of the Amygdala in Anxiety Disorders

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Additional information is available at the end of the chapter

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1. Introduction

1.1. Defining anxiety and fear

Anxiety is a term often used to encompass feelings of apprehension, dread, unease or similarly unpleasant emotions. Trait anxiety defines the affect of an organism over time and across situations, whereas state anxiety is the response or adaptation to a given situation [1]. Anxiety can be differentiated from fear, both biologically and behaviorally [see 1 for an extensive review]. Converging theories and evidence from clinical psychology and comparative neuroscience suggest that fear can be considered a negatively-valenced emotion that is brief, focused on the present, occurs in situations of specific threat, and aids in avoidance or escape [1,2]. Anxiety, on the other hand, is a negatively-valenced emotion that is characterized by sustained hyperarousal in response to uncertainty, is thus future-focused, and aids in defensive approach or risk assessment [1,2]. Both anxiety and fear are emotions experienced by all individuals and can serve to be adaptive in shaping decisions and behaviors related to survival of an organism [1,3]. However, when excessive, or pathological, or triggered inappropriately, fear and anxiety form the basis of a variety of anxiety disorders [3,4,5; Table 1]. As illustrated by Table 1, some anxiety disorders such as generalized anxiety disorder (GAD) or obsessive-compulsive disorder (OCD) are characterized by excessive anxiety as defined above [1]. However, other anxiety disorders are characterized, at least in part, by excessive and inappropriate fear, such as posttraumatic stress disorder (PTSD), specific phobias and social anxiety disorder [1,3; Table 1]. Thus, it is important to understand the neurobiology of both anxiety and fear to obtain a comprehensive picture of the physiological basis of anxiety disorders.

1.2. Anxiety disorders

One in three people will develop one of the anxiety disorders outlined by Table 1 within their life-time, with the life-time prevalence at least two times more likely for women [5,6].

Furthermore, individuals may present with one or more comorbid anxiety disorders, and anxiety disorders are highly likely to be comorbid with other psychiatric illnesses, such as major depressive disorder, psychosis, mania, and substance abuse disorder [4-6]. Several non-psychiatric disorders are also associated with anxiety disorders, and these include hyperthyroidism, Cushing's disease and mitral value prolapse [4,5]. Thus, anxiety disorders are one of the most prevalent psychiatric disorders, posing great personal, economic, and societal burdens [4-6].

Generalized Anxiety Disorder (GAD)
Excessive worry occurring more days than not over at least a 6 month period, accompanied by restlessness, fatigue, sleep disturbances, muscle tension or irritability.
Posttraumatic Stress Disorder (PTSD)
Characterized by a history of trauma and symptoms related to avoidance, re-experiencing, and physiological hyperarousal in the face of triggering cue.
Obsessive-Compulsive Disorder (OCD)
Compulsions (repeated actions) produced to reduce anxiety associated with obsessions (unwanted, intrusive thoughts).
Panic Disorder
Characterized by panic attacks; a period of intense fear or discomfort accompanied by a variety of physiological symptoms (e.g. sweating, trembling, chest pains, tachycardia).
Agoraphobia
Fear and avoidance of situations from which escape would be difficult in the event of having panic-like symptoms.
Specific Phobia
Excessive or unreasonable fear in anticipation or in response to a specific object or situation.
Social Anxiety Disorder (Social Phobia)
Excessive/unreasonable fear and avoidance of social situations (including performances) in which the person is exposed to unfamiliar people or possible scrutiny by others.

Table 1. Major Classes of Anxiety Disorders [4,5,7]

1.3. Goals of the current review

The neurobiological bases of anxiety and fear appear to be very similar across species [1], thus complementary findings from both animal models (most often rodents) and human studies can contribute to theories of the neurobiological basis of anxiety disorders. State fear within animal models is most often studied by measures of freezing and fear-potentiated startle, both acquired via classical conditioning of rodents [1,8]. State anxiety, on the other hand, is most often studied using apparatus such as an open field, elevated plus maze, or light-dark box, which all take advantage of the rodent's preference for familiar, dark, and/or enclosed areas [1,9]. Notably, these paradigms do not rely on the processes underlying classical conditioning, although McNaughton and Corr [2] caution against defining fear verses anxiety as conditioned versus unconditioned responses. While trait fear is not well-defined by animal studies [1], trait anxiety is often examined in animal models by the use of selective breeding, resulting in high- and low-anxiety strains and lines of rodents [for example, see 1, 10]. However, one can argue that experimental manipulations (such as early-life stress or amphetamine withdrawal) that drive a group of animals towards greater fear- and anxiety-like phenotypes also examine the underlying basis of trait fear or anxiety [e.g. 11, 12]. As noted by Sylver et al [1] clinical studies most often examine trait anxiety, whereas experiments involving animal models most often focus on state anxiety and fear, and then relate these findings to concepts associated with trait anxiety. Regardless, both human and animal studies suggest an important role for the amygdala, and subregions within, in mediating fear and anxiety, and in the manifestation of anxiety disorders (Sections 2 and 3). Therefore, the goals of this review are to first evaluate and integrate classical and recent findings from human studies and relevant animal models that reveal the specific role the amygdala plays in fear and anxiety, and then to elucidate how anxiolytic drugs may affect the amygdala function to ameliorate heightened fear and/or anxiety. This is important, given that traditional drug and cognitive behavioral therapy (CBT) are effective in reducing symptoms of the various anxiety disorders for many individuals, but often do not provide long-term relief, and relapse is a common post-treatment outcome [as reviewed by 3]. Therefore, the final goal of the current review is to identify future potential therapeutic targets for the treatment of anxiety disorders.

2. Human imaging studies: Amygdala hyperfunction and anxiety disorders

2.1. Amygdala reactivity and anxiogenic or fearful stimuli

Human imaging studies that explore the neurobiological bases of anxiety or fear processing typically use functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) as measures of neural activity or cerebral blood flow. Imaging experiments that are designed to study neural reactivity to fearful stimuli utilize either conditioned fear paradigms similar to those used in animal models, or involve the presentation of unconditioned stimuli such as fearful faces [1]. It has become clear that masked stimuli can elicit conditioned and unconditioned fear responses from human subjects, suggesting unconscious, implicit processing of these cues [as reviewed by 1]. Similarly, increased activity of the amygdala is observed in response to both conditioned and unconditioned fearful stimuli, independent of whether the subject is aware of the stimulus [1,13-16].

Comparable studies that have examined neural correlates of anxiety in healthy controls are limited. One of the reasons for this is that many studies use fearful stimuli, such as the fearful faces or conditioned fear paradigms [1], blurring the distinction between fear and anxiety. Therefore, conclusions regarding neural bases of anxiety are better drawn from studies that include trait anxiety as a variable while utilizing fearful stimuli, or those fewer studies in which an anxiogenic situation is created within the experimental design. Like for studies of fear processing, the majority of these studies show a relationship between trait anxiety and greater amygdala reactivity [as reviewed by 17]. For example, a study of healthy subjects found that reactivity of the amygdala was positively correlated with anticipatory anxiety, and when the anticipated event was imminent, amygdala activation positively correlated with the degree of trait anxiety [18]. Furthermore, college students who scored in the upper 15th percentile for trait anxiety show greater amygdala reactivity to emotional faces as compared to students who scored in the normative range, suggesting that anxiety-prone individuals have greater amygdala reactivity [19]. A similar hyperactivity of the amygdala in high trait anxiety participants is noted when a masked emotional faces or unattended faces paradigm are used [20,21], suggesting the individual does not need to be aware of the stimulus to exhibit heightened amygdala activity. Interestingly, Etkin et al., [21] differentiate between different subregions of the amygdala (see Section 3.1 for more details on amygdala subregions), with the basolateral amygdala activated during masked presentations of emotional faces while the dorsal/central amygdala was activated during unmasked presentations. Thus, there may be subregion specificity within the amygdala when processing unconscious versus conscious emotionally-valenced stimuli.

When gender has been examined as a factor in populations of healthy subjects, higher trait anxiety is associated with greater amygdala responses to unattended fearful faces in female but not male participants [22]. A further factor potentially mediating the relationship between trait anxiety and amygdala reactivity appears to be perceived social support. To illustrate, Hyde et al. [17] show a positive correlation between the degree of trait anxiety and amygdala reactivity to fearful faces in subjects that report below-average social support, but not in those who report above average support. Related, it is also thought that the degree of social anxiety rather than trait anxiety may be more closely related to amygdala reactivity to emotional faces [23]. These factors, and other similar considerations, may explain why some, but not all, studies show a positive correlation between trait anxiety and amygdala reactivity in non-patient populations [18-21,23].

2.2. Amygdala reactivity in anxiety disorders

Hyperactivity of the amygdala in response to negatively-valenced stimuli also appears to be a common finding from a variety of clinical anxiety populations [16]. For example, individuals suffering from social anxiety disorder show heightened amygdala responses to both social and non-social highly emotive stimuli as compared to healthy control groups, with the degree of social anxiety positively correlated with amygdala reactivity [24-27]. Furthermore, activation of the amygdala by non-social stimuli has been correlated with trait anxiety in social anxiety disorder, leading to the conclusion that social anxiety disorder is characterized by a more general dysfunction in emotional processing in addition to altered processing of social stimuli and situations [26]. Importantly, reduced symptoms in a public speaking situation following either CBT or antidepressant treatment was associated with reduced amygdala reactivity [24], further suggesting a tight link between symptomology and amygdala reactivity in social anxiety disorder.

Like social anxiety disorder, a commonly replicated finding from various PTSD populations is hyperactivity of the amygdala in response to masked fearful faces or trauma-related stimuli [3,28,29]. This manifests as higher amygdala reactivity as compared to non-PTSD groups and/or a positive correlation between severity of PTSD symptoms and amygdala reactivity [28,30-33]. Furthermore, in a group of unmedicated acute PTSD subjects (1 month post trauma), the degree of PTSD symptoms also positively correlated with activity of the amygdala in response to masked fearful faces [34]. Thus, amygdala hyperactivity observed in chronic PTSD appears early in the disorder. However, it should be noted that in these same individuals, the degree of PTSD symptoms negatively correlated with activity in the amygdala in response to unmasked fearful faces [34]. This suggests amygdala hypoactivity in response to consciously-processed fearful stimuli in the early stages of PTSD, further implying a dissociation in amygdala activity in response to consciously-processed versus unconsciously-processed fearful stimuli. Interestingly, activity of the amygdala in response to fearful stimuli might not only be characteristic of PTSD, but might predict treatment outcome. Bryant et al [33] show that individuals diagnosed with PTSD that do not respond to CBT (8 one weekly sessions) show significantly greater pre-treatment amygdala activation in response to masked fearful faces as compared to those PTSD subjects who did respond to CBT, as defined by a 50% or more reduction in scores on the Clinician-Administered PTSD Scale (CAPS). Therefore, hyper-function of the amygdala might provide a useful tool for future selections of treatment options for PTSD.

Similar to PTSD and social anxiety disorder, amygdala hyperactivity as a result of highly emotional stimuli presentation or symptom provocation has been observed in specific phobia, panic disorder, and OCD [35-38]. Given the prevalence of GAD, it is surprising that few studies have assessed amygdala reactivity in GAD participants. Somewhat more surprising is that of those studies that have determined amygdala activity in response to emotive stimuli in adult GAD populations, a lack of amygdala hyperactivity has been observed [27,39,40]. This stands in contrast to findings from pediatric GAD, where hyperactivity of the amygdala is apparent in response to emotional stimuli and positively correlated with symptom severity [41,42]. However, recent findings examining amygdala function within paradigms that elicit anticipatory anxiety or emotional conflict have implicated a role for amygdala hyper-reactivity in adult GAD populations. For example, Nitschke et al. [43] report greater anticipatory amygdala activation in response to both emotional and neutral images in adult GAD subjects. Furthermore, Etkin et al [44] found that adult participants with GAD exhibited poor performance on a task that involved emotional conflict (incongruent visual emotional stimuli), accompanied by a failure of the frontal cortex to exert negative top-down control of amygdala activity (see Section 3.1 for more on top-down control of the amygdala). Therefore, amygdala hypofunction in adult GAD might be better revealed by imaging studies that create anxiogenic or conflict situations, rather than the standard presentation of fearful stimuli. While this conclusion requires direct testing, the findings that anxiogenic but not fearful stimuli reveal hypofunction of the amygdala in GAD, whereas fearful stimuli consistently elicit amygdala hyper-reactivity in other anxiety disorders (such as social anxiety disorder, PTSD and also pediatric GAD), suggests a neural dichotomy between GAD and other anxiety disorders on the anxiety to fear continuum.

In summary, there appears to be reasonable overlap across various experimental paradigms and study populations to conclude that the amygdala is reactive to fearful stimuli and anxiogenic situations, and exhibits hyper-function to emotive stimuli, anxiogenic situations and/or symptom provocation in anxiety disorders. However, which neurotransmitters and subregions of the amygdala mediate these responses if often better answered by animal studies, where spatial and neurochemical resolution is greatly improved over human imaging studies.

3. Amygdala subregions, connectivity, neurotransmission and fear/anxiety

3.1. The role of amygdala subregions in mediating fear and anxiety

As discussed above, hyper-function of the amygdala appears to be a key component of human anxiety disorders. However, the contribution of particular amygdalar subregions in the development and maintenance of this hyperactive state in humans is still being established. Only very recently have refinements in the acquisition and analysis of fMRI data allowed subregion function to be segregated effectively during emotional tasks such as avoidance learning [45] and facial expression recognition [21,46]. Similarly, effective structural identification of human amygdalar subregions and assessment of their functional connectivity using imaging techniques is still fairly new [for example, see 47-51]. Therefore, most of our understanding of causal neurochemical pathways in amygdalar circuitry related to fear and anxiety has derived from extensive studies using rodent and non-human primate models [for example, see 9,52-58].

Anatomical arrangement of the mammalian amygdala appears to have been evolutionarily conserved, with particular subregions being connected to homologous brain structures across species [as reviewed by 59]. The lateral (LA) nucleus of the amygdala is reciprocally connected with the auditory, somatosensory and visual sensory association centers in the temporal and insular cortices [59], and in rats also receives further auditory information via projections from the posterior thalamus [59,60]. The medial amygdala (MeA) is reciprocally connected with the accessory olfactory bulb and many hypothalamic and preoptic nuclei [59,61], creating a locus for assimilation of olfactory stimuli and information regarding internal hormonal state [62,63]. Information summated within the LA and MeA is then conveyed to the adjacent basal (B) and accessory basal (AB) nuclei [64], which also receive projections from the CA1 and subiculum areas of the ventral hippocampus [65-67]. The B/AB nuclei send excitatory and inhibitory projections back to the LA and MeA [64,68], creating a localized circuit that may assist in fine-tuning the filtering of sensory input into these regions [64]. Excitatory projections from this basolateral (BLA) complex target the central nucleus of the amygdala (CeA) either directly or via a series of GABAergic interneurons known as intercalated (ITC) cells located between the BLA and CeA [69], providing an effective means of gating CeA activity and output through a combination of direct excitation and feed-forward inhibition [64,70,71]. The CeA itself, principally the medial sector, sends GABAergic projections to brainstem, hypothalamic and basal forebrain regions that control expression of autonomic, hormonal and behavioral responses to emotive situations 72,73]. It should also be noted that in addition to activating the CeA, the BLA projects to the adjacent bed nucleus of the stria terminalis (BNST), which in turn targets many of the same regions as the CeA to produce similar behavioral and physiological responses [73]. The MeA is also able to regulate these responses not only via its influence on hypothalamic nuclei and brainstem targets, but by modulating activity in the BNST and CeA [61,64].

The functional connectivity between the BLA, MeA and CeA ensures that sensory and contextual information associated with emotional situations, such as fearful or anxiogenic circumstances, is channeled to effector regions to produce appropriate responses necessary for survival. The BLA and CeA, unlike the MeA, do not appear necessary for expression of unconditioned fear responses to olfactory stimuli in rodents, e.g., to novel presentation of predator odor [74-76], although the BLA does appear to play a role in responses to other types of unconditioned stimuli [77,78]. However, the functional arrangement of the BLA and CeA with other regions facilitates learning about the situation, such that appropriate reactions are maintained if cues associated with initial exposure are experienced again. The BLA in particular appears to play a crucial role in encoding positive or negative salience to relevant stimuli for future reference, as indicated by numerous studies showing that the BLA is required for fear learning and acquisition of conditioned fear responses [see 56,60]. Once fear conditioning is acquired, the CeA is necessary for expression of the conditioned response [56,60], the magnitude of which will be influenced by BLA gating of CeA activity and output. Similarly, the BLA is needed for acquisition and expression of fear extinction [79,80], which requires a subject to learn that expression of a previously conditioned fear response is no longer necessary when the conditioned stimulus no longer predicts an aversive event [57,81]. To achieve this, the BLA must integrate new sensory information (absence of the unconditioned aversive stimulus) that will result in a dampening of CeA excitation. This may result from increased BLA excitation of ITC cells during fear extinction acquisition to enhance feed-forward inhibition of the CeA [79,82,83], followed by structural remodeling within the BLA during consolidation of the extinction memory to inhibit later BLA output [79]. However, while the roles of the BLA and CeA in fear behaviors are well established, their contribution to anxiety is less clear, especially for the CeA. Animal studies suggest that changes in BLA and CeA activity can alter state anxiety [9; also see Section 3.2.]. However, most investigations have focused on the BLA with the exact role of the CeA remaining ill-defined [for example, see 84,85], although it appears that BLA to CeA circuitry can directly regulate anxiety-like behavior as measured on the elevated plus maze [EPM, 86]. This direct control is thought to result from BLA excitation of GABAergic neurons in the lateral CeA to induce feed-forward inhibition of output from the medial CeA [86], similar to that induced by BLA excitation of ITC cells during fear extinction. Thus, suppression of CeA output may be equally important for mediating expression of both fear and anxiety. Alternatively, some studies have suggested that it is BLA activation of the BNST, not of the CeA, that is responsible for mediating anxiety-like behavior as measured using light-potentiated startle responses in rodents [56,87,88]. Startle responses are also potentiated by corticotropin releasing factor (CRF) infused into the BNST [56]. This effect is presumed to result through facilitation of glutamate release from BLA afferents by CRF neurons that originate in the lateral CeA [88,89], implying that even if BNST is the principal output center for certain types of anxiety-like behaviors, the CeA may still play some modulatory role. Furthermore, the MeA has been strongly implicated in animal models of state anxiety [for example, see 90-93 and see Section 3.2], but whether its effects involve modulation of CeA activity is unknown. To direct translational research into the neurological underpinning of anxiety disorders more effectively, animal studies employing as wide a range of state anxiety paradigms as possible, along with animal models that generate trait anxiety, are required to establish the exact nature of CeA involvement and of amygdala subregion interplay in mediating anxiety-like behavior.

It is important to remember that while the amygdala can mediate fear and anxiety-like behavior, other brain regions play a major role in expression of these states, presumably by influencing activity in particular amygdalar subregions to alter the balance of output from the CeA. For example, input from the ventral hippocampus to the B/AB nuclei within the BLA is required for expression of conditioned fear responses to contextual cues in rodents and humans [60,94,95], and so receipt of this information presumably increases BLA activity, to in turn enhance CeA output in the aversive context. In rodents, the ventromedial prefrontal cortex (vmPFC) also appears to be crucial in regulating amygdalar activity, especially during fearful experiences [79]. The prelimbic (PL) subregion of the vmPFC can enhance conditioned fear expression via excitatory projections to the BLA and CeA [96-98]. In contrast, expression of conditioned fear appears to be decreased by activation of the infralimbic (IL) subregion of the vmPFC [99, but see 100]. The IL cortex is also required for effective consolidation and recall of fear extinction memories [79,98]. Both decreased conditioned fear responding and fear extinction require suppression of CeA output, which is thought to result in part via IL cortex stimulation of the series of inhibitory ITC cells that project to the CeA [71,79,96,101]. The bidirectional roles of the PL and IL cortices in regulating conditioned fear through opposing influences on CeA activity and output imply that imbalance in the influence of either cortical structure could contribute to amygdala hyperactivity seen in anxiety disorders characterized by excessive and inappropriate fear (see Table 1). This is supported by fMRI studies investigating neural correlates of impaired fear extinction in PTSD patients, who compared to healthy subjects show hyperactivity of the amygdala during extinction learning [102]. This enhanced amygdala function in PTSD patients is accompanied by greater activation of the dorsal anterior cingulate cortex (dACC, functionally equivalent to the rodent PL cortex, [3,57], which is also present during recall of the extinction memory [102]. This is in line with rodent studies demonstrating potentiated fear conditioning upon PL cortex activation [98]. However, PTSD individuals exhibit hypoactivation of the ventral portion of the vmPFC (equivalent to rodent IL cortex, [3,57]) during extinction learning and recall [102,103]. Human imaging studies also suggest that impaired regulation of amygdala activity by the ventral vmPFC may contribute to anxiety disorders characterized by hypervigilance in the absence of conditioned stimuli, such as in GAD. Specifically, the strength of the connection between the vmPFC and the amygdala, as measured using diffusion tensor imaging, predicts levels of self-reported trait anxiety, such that weaker connections are seen in more anxious individuals [104]. As mentioned earlier (Section 2.2), participants with GAD exhibited a failure of the vmPFC to exert negative top-down control of amygdala activity during a task that involved emotional conflict [44]. Further, resting state fMRI revealed that in anxious individuals, vmPFC activity was negatively correlated with amygdala activity, while a positive relationship was observed for low anxious subjects [105]. The combination of animal and human studies strongly indicates that inadequate suppression by the ventral portion of the vmPFC, most likely of the CeA, is a key factor in amygdala hyperactivity underlying the emergence of excessive fear and anxiety states.

3.2. Monoaminergic neurotransmission in the amygdala: Relation to fear and anxiety

The monoamine neurotransmitters (serotonin, dopamine and norepinephrine) have long been associated with fear and anxiety, and drugs that alter monoaminergic function are often effective across the range of anxiety disorders [8, 9, 52, 55]. Animal studies suggest a variety of anxiogenic stressors or fearful stimuli increase monoamine levels in the amygdala. To illustrate, increased serotonin (5-HT) release or increased activity of 5-HT neurons in the amygdala have been observed in response to restraint or footshock, or in association with expression of conditioned fear behavior [106-110]. Similarly, dopamine (DA) and norepinephrine (NE) levels in the amygdala are increased following restraint, handling stress, footshock or during the expression of conditioned fear behavior [107,111-118]. The source of monoamines to the amygdala arise from monoaminergic cell body regions in the brainstem. Specifically, the dorsal raphe nucleus (dRN) provides 5-HT innervation to the amygdala, while NE and DA innervation of the amygdala arise from the locus coeruleus (LC) and ventral tegmental area (VTA) respectively [55,119,120]. Regulation of monoaminergic activity in the amygdala thus can occur at the level of these brainstem cell body regions, or within the terminal regions of the amygdala.

One of the important mediators of amygdala monoaminergic activity in response to anxiogenic or fearful stimuli is CRF. A strong body of evidence implicates central CRF in mediating fear and anxiety [12,121-128], and recent clinical studies suggest an important role for CRF in anxiety disorders [129]. Like anxiogenic and fearful stimuli, central infusion of CRF or CRF receptor agonists increases 5-HT, NE and DA levels in the amygdala [130-133], and stress-induced increases in monoamine levels in the amygdala are prevented by CRF receptor antagonists [108,111]. It is thought that CRF regulation of monoaminergic activity in the amygdala occurs at the level of the monoaminergic cell bodies. The monoaminergic cell body regions receive CRF innervation from the CeA and BNST, and CRF type 1 and 2 (CRF_1 and CRF_2) receptors are localized to the dRN, LC and VTA [134-140]. Direct infusion of CRF or CRF receptor agonists into the dRN stimulates 5-HT release in the CeA or BLA [131-133]. Interestingly, CRF-induced 5-HT release in the amygdala appears to be dependent on CRF_2 receptor activation in the dRN [131,133], and CRF_2 receptors are known to increase 5-HT neuronal firing rates in the dRN [141]. Importantly, increased neuronal surface expression of CRF_2 receptors occurs in the dRN as a result of stress [142], and increased expression of CRF_2 receptors in the dRN has been observed in rat models of high anxiety [11,128,137,143]. Furthermore, CRF_2 receptor antagonists infused directly into the dRN reduce heightened anxiety-like behavior in rat models of amphetamine withdrawal or early life stress [12,128]. Combined, these findings suggest that CRF_2 receptor modulation of 5-HT activity in the amygdala may play an important role in heightened anxiety. While similar studies have not been performed to elucidate the role of CRF receptors in the LC and VTA in mediating NE and DA activity in the amygdala and anxiety states, some indirect evidence suggests an important role for CRF receptors in the LC and VTA stress responses [136,138,144]. Overall, it is clear that further investigations are needed to ascertain the role of CRF receptors in mediating NE and DA activity in the amygdala and how CRF modulation of this activity could relate to fear or anxiety.

Studies demonstrating increased monoamine activity in the amygdala in response to anxiogenic or fearful stimuli, and CRF modulation of these responses (as described above) do not allow conclusions to be made about the specific role of each monoamine in mediating anxiety or fear. Direct manipulation of monoaminergic activity within the amygdala or specific amygdala subregions, and the measurement of resultant anxiety-like or fear-related behaviors, have gone some way to providing a picture of how monoamine function in the amygdala might translate to anxiety or fear. Table 2 summarizes such studies directly manipulating 5-HT levels or 5-HT receptor activity in the amygdala. When 5-HT or 5-HT activity is decreased in the entire amygdala [145,146], a consistent increase in anxiety-like behavior is observed (Table 2). This would suggest that increased 5-HT activity in the amygdala would thus be associated with decreased anxiety, implying an anxiolytic role of 5-HT. However, this does not appear to be supported by experiments that directly manipulate 5-HT receptor activity in the amygdala with 5-HT receptor ligands (Table 2). For example, activation of postsynaptic excitatory 5-HT_2 or 5-HT_3 receptors in the amygdala decreases social interaction and increases anxiety-like behavior, whereas antagonism of 5-HT_3 receptors in particular increases social interaction and decreases anxiety-like behaviors, suggesting that 5-HT actions on postsynaptic receptors is anxiogenic (Table 2), although, see [147] for an exception to this pattern. Similarly, activation of excitatory $5HT_2$ receptors in the BLA generally increases anxiety-like behavior (Table 2), suggesting an anxiogenic role for postsynaptic 5-HT receptors in the BLA (although an exception to this is observed, [148]). In contrast, inhibitors of 5-HT_2 receptors in the MeA increase anxiety-like behavior while activation of these receptors increases social interaction and decreases anxiety behavior (Table 2). Thus like the some findings from the amygdala as a whole (Table 2), 5-HT activity in the MeA appears to play an anxiolytic role. The role of 5-HT or 5-HT receptors has not been well studied in the CeA. However, rats undergoing amphetamine withdrawal that exhibit greater anxiety-like behavior have greater 5-HT release in the CeA [12,133], suggesting a similar anxiogenic relationship between 5-HT and anxiety as for the BLA. Future work should determine whether 5-HT in the CeA reduces anxiety-like behaviors as is suggestive for the MeA, or in contrast, increases anxiety-like behaviors as appears to be the case for the BLA. Overall, the findings summarized in Table 2 suggest a dichotomy in the potential role of 5-HT in the amygdala in mediating anxiety depending on whether the entire amygdala or a specific subregion is targeted. Potential confounds in comparing the studies listed in Table 2 could be the different paradigms used to measure anxiety-like behaviors and the relative selectivity of 5-HT receptor ligands across different experiments. Future studies directly comparing the effects of 5-HT manipulations within the different amygdala subregions across several well-validated tests of anxiety-like behaviors will better elucidate the role of amygdala 5-HT in mediating anxiety.

Amygdala Subregion	Monoamine or Receptor Involvement	Behavioral Outcome	Citation
Anxiety-like Behavior			
Amygdala	Decreased 5-HT (induced by MDMA)	Increased anxiety behavior	Faria et al. [145]
Amygdala	Decreased 5-HIAA (induced by stress)	Increased anxiety behavior	Niwa et al. [146]
Amygdala	5-HT_{1A} agonist	No change in anxiety behavior	Zangrossi and Graeff [149]
Amygdala	$5\text{-HT}_{2B/2C}$ agonist	Increased anxiety behavior	Cornelio and Nunes-De-Souza [150]
Amygdala	5-HT_{3} agonist	Decreased social interaction	Higgans et al. [151]
Amygdala	5-HT_{3} agonist	Decreased anxiety behavior	Costall et al. [147]
Amygdala	5-HT_{3} antagonist	Increased social interaction	Higgans et al. [151]
Amygdala	5-HT_{3} antagonist	Decreased anxiety behavior	Costall et al. [147]
Amygdala	5-HT_{3} antagonist	Decreased anxiety behavior	Tomkins et al. [152]
BLA	5-HT_{1A} agonist	Decreased social interaction	Gonzalez et al. [153]
BLA	5-HT_{1A} agonist	No change in anxiety behavior	Gonzalez et al. [153]
BLA	5-HT_{2A} agonist	Increased anxiety behavior	Zangrossi and Graeff [149]
BLA	$5\text{-HT}_{2A/2C}$ agonist	No change in anxiety behavior	Cruz et al [148]
BLA	5-HT_{2C} agonist	Increased anxiety behavior	Vincente et al. [154]
MeA	5-HT_{2A} antagonist	Increased anxiety behavior	Zangrossi and Graeff [149]
MeA	5-HT_{2} agonist	No change in anxiety behavior	Duxon et al. [155]
MeA	5-HT_{2B} agonist	Increased social interaction	Duxon et al. [156]
MeA	5-HT_{2B} agonist	Decreased anxiety behavior	Duxon et al. [155]

Amygdala Subregion	Monoamine or Receptor Involvement	Behavioral Outcome	Citation
MeA	5-HT$_{2B/2C}$ agonist	No change in anxiety behavior	Duxon et al. [155]
Fear-related Behavior			
CeA	Increased 5-HT	Increased unconditioned freezing	Forster et al. [132]
BLA	Increased 5-HT	Decreased conditioned freezing	Inoue et al. [157]
BLA	Increased 5-HT	Decreased unconditioned tonic immobility	Leite-Panissi et al. [158]
BLA	5-HT$_{1A}$ agonist	Decreased conditioned freezing	Li et al. [159]
BLA	5-HT$_{1A}$ agonist	Decreased acquisition and expression of conditioned defeat	Morrison et al. [160]
BLA	5-HT$_{1A/2}$ agonist	Decreased unconditioned tonic immobility	Leite-Panissi et al. [158]

Abbreviations: 5-HIAA = 5-Hydroxyindoleacetic acid (5-HT metabolite); 5-HT = serotonin; BLA = basolateral amygdala; CeA = central nucleus of the amygdala; MDMA = 3,4-methylenedioxy-N-methylamphetamine; MeA = medial amygdala.

Table 2. The Role of Serotonin in Anxiety-Like and Fear-Related Behaviors

Determining the role of amygdala 5-HT in fear-related behavior has mainly utilized studies of freezing or immobility responses in rodents, and of 5-HT manipulation in the BLA (Table 2). From these studies, it seems clear that 5-HT in the BLA decreases the expression of unconditioned and conditioned fear responses, likely via activation of the inhibitory postsynaptic 5-HT$_{1A}$ receptor (Table 2). Thus, it has been suggested that 5-HT in the BLA/amygdala ameliorates fear [8]. This conclusion is in contrast to the apparent role for BLA 5-HT in enhancing anxiety (Table 2), suggesting a fear versus anxiety dissociation for the role of 5-HT in the BLA. This dissociation, if upheld by more in-depth future work, could prove important information for the development of treatment strategies for the various anxiety disorders that differ in the degree of anxiety-like and fear-like symptomology (as discussed in Section 1.1).

A role for amygdala DA in anxiety has not been as well explored as for 5-HT. However, a summary of studies that have manipulated DA function in the amygdala provides a consistent picture of the role of amygdala DA in mediating anxiety in animal models (Table 3). Indirect evidence suggests that decreased DA in the amygdala leads to increased anxiety, and this is supported by direct manipulation of the CeA (Table 3). For example, decreased DA or DA receptor antagonism within the CeA all increase anxiety-like behavior (Table 3), suggesting that DA activity in the CeA is anxiolytic. This role for DA in the CeA is in direct contrast to the BLA, where converging evidence suggests that decreased DA function in the BLA decreases anxiety-like behaviors while increased DA receptor activity in the BLA increases anxiety (Table 3). Thus, DA activity in the BLA is anxiogenic, revealing an opposite role for DA activity in the CeA and BLA in mediating anxiety-like behaviors in animal models.

Amygdala Subregion	Monoamine or Receptor Involvement	Behavioral Outcome	Citation
Anxiety-like Behavior			
Amygdala	Decreased DA	Decreased rearing in open field indicative of increased anxiety behavior	Summavielle et al. [163]
CeA	Decreased DA	Decreased voluntary activity indicative of increased anxiety behavior	Izumo et al. [164]
CeA	D_1 antagonist	Increased anxiety behavior	Rezayof et al. [165]
CeA	$D_{2/3}$ antagonist	Increased anxiety behavior	de la Mora et al. [166]
BLA	DA depletion	Decreased anxiety in males but not females	Sullivan et al. [167]
BLA	D_1 agonist	Increased anxiety behavior	Banaej et al. [168]
BLA	D_2 agonist	Increased anxiety behavior	Banaej et al. [168]
BLA	D_1 antagonist	Decreased anxiety behavior	Banaej et al. [168]
BLA	D_1 antagonist	Decreased anxiety behavior	de la Mora et al. [169]
BLA	D_2 antagonist	Decreased anxiety behavior	Banaej et al. [168]
Fear-related Behavior			
Amygdala	D_2 antagonist	Decreased acquisition and retention of fear conditioning	Greba et al. [170]
CeA	D_1 agonist	Increased conditioned fear behavior	Guarraci et al. [171]
CeA	D_1 antagonist	Inhibited conditioned fear behavior	Guarraci et al. [171]
CeA	D_2 antagonist	Decreased	Guarraci et al. [172]

Amygdala Subregion	Monoamine or Receptor Involvement	Behavioral Outcome	Citation
		conditioned fear behavior	
BLA	DA depletion	Decreased fear conditioning	Seldon et al. [173]
BLA	D_1 antagonist	Inhibited acquisition of fear conditioning	Greba and Kokkinidis [174]
BLA	D_2 antagonist	Inhibited fear potentiated startle	De Oliveira et al. [175]

Abbreviations: BLA = basolateral amygdala; CeA = central nucleus of the amygdala; DA = dopamine.

Table 3. The Role of Dopamine in Anxiety-Like and Fear-Related Behaviors

In contrast, the role of DA in mediating fear-related behaviors does not appear to differ based on amygdala subregion (Table 3). Reducing DA function in the amygdala reduces or inhibits processes associated with fear conditioning, while increasing DA receptor activity increases conditioned fear (Table 3). Thus, DA in the amygdala is required for fear conditioning, and enhanced DA levels in the amygdala as elicited by fearful stimuli and conditioned cues [107,112] would thus facilitate fear conditioning. It should be noted that the studies summarized by Table 3 indicate a role for both excitatory D_1 receptors and inhibitory D_2 receptors. Dopamine D_2 receptors are localized both pre- and post-synaptically, with pre-synaptic D_2 autoreceptors limiting DA neuronal activity and DA release [161,162]. Thus, antagonism of presynaptic D_2 receptors would actually increase DA within the amygdala. Since the effects of D_2 receptor antagonism on fear-related behaviors is characteristic of reduced, not enhanced, DA function in the amygdala, it may be concluded that the results of D_2 receptor antagonism summarized by Table 3 are due to postsynaptic D_2 receptor effects. However, this conclusion requires direct testing.

Very few studies have examined the role of amygdala NE in mediating anxiety-like behavior in animal models, surprising given that anxiogenic stimuli increase NE in this region [for example, see 111,115,116] and drugs that alter NE neurotransmission are used to treat anxiety disorders [8]. There appears to be little role for NE receptors in the CeA in mediating anxiety-like behavior, although infusion of a α_1 antagonist can increase social interaction following an anxiogenic stimulus [restraint; 176; Table 4]. It is clear that more experiments are required to delineate the role of amygdala NE in mediating anxiety.

Studies determining the role of NE in fear-related behaviors have concentrated on the BLA, due to the importance of this amygdala subregion in conditioned fear responses (see Section 3.1.). The major focus of the studies summarized by Table 4 has been on the role of NE in fear conditioning and reconsolidation of fear memories in conditioned fear paradigms. Taken as a whole, findings suggest that NE in the BLA facilitates fear conditioning and fear memory, via activation of adrenergic β receptors (Table 4). Recent evidence suggests a role for α_1 receptors in the BLA in mediating fear memory, in this case, activation of α_1 receptors by NE would appear to decrease fear memory (Table 4). Thus, it is possible that NE in the

BLA could have opposing effects on reconsolidation of fear memory based on the balance of α_1 versus β receptor activity – a hypothesis that requires direct testing. The role of NE in the BLA (and β receptors in particular) in fear memory has generated interest in targeting this NE system for the treatment of anxiety disorders where enhancement in fear memory is apparent, such as PTSD [for example, see 177]. Whether NE within the BLA plays a role in other aspects of fear processing (e.g. unconditioned fear responses to non-olfactory based stimuli) or NE within other amygdala subregions mediate fear should be subjects of future investigations to fully elucidate the role of amygdala NE in fear.

Amygdala Subregion	Monoamine or Receptor Involvement	Behavioral Outcome	Citation
Anxiety-like Behavior			
CeA	α_1 antagonist	Increased social interaction	Cecchi et al. [176]
CeA	α_1 antagonist	No effect on anxiety behavior	Cecchi et al. [176]
CeA	$\beta_{1/2}$ antagonist	No effect on social interaction	Cecchi et al. [176]
CeA	$\beta_{1/2}$ antagonist	No effect on anxiety behavior	Cecchi et al. [176]
Fear-related Behavior			
BLA	Increased NE	Increased memory and retention of fear conditioning	LaLumiere et al. [178]
BLA	Decreased NE	Impaired fear conditioning	Seldon et al. [173]
BLA	Decreased NE	Impaired fear memory	Debiec and LeDoux [177]
BLA	α_1 antagonist	Increased fear memory	Lazzaro et al. [179]
BLA	$\beta_{1/2}$ antagonist	Impaired of fear memory	Debiec and LeDoux [180]
BLA	β_1 antagonist	Impaired fear memory (as enhanced by glucocorticoids)	Roozendaal et al. [181]

Abbreviations: BLA = basolateral amygdala; CeA = central nucleus of the amygdala; NE = norepinephrine.

Table 4. The Role of Norepinephrine in Anxiety-Like and Fear-Related Behaviors

In summary, it is clear that more work is required to fully understand the role of amygdala monoamines in mediating fear and anxiety. However, several patterns of interest emerge from the current literature, namely that there are distinct subregion differences in the role each monoamine plays in mediating anxiety and fear, with the one monoamine possibly playing opposing roles depending on subregion or depending on whether anxiety or fear measures are employed. Therefore, these findings suggest neurochemical dissociations between amygdala subregions and monoamines in mediating fear or anxiety.

4. The amygdala as a potential site of anxiolytic drug action

Psychopharmacological management of anxiety disorders includes the benzodiazepines, antidepressants, 5-HT_{1A} agonists and various "off-label" drugs such as β-blockers, mood stabilizers and antipsychotics. The mechanism by which these drugs produce anti-anxiety effects has yet to be definitively established and represents a frequently updated field of research. Because these drugs bind to target receptors throughout the brain, it is unlikely that their efficacy can be attributed to action in one particular region. However, given the role that the amygdala plays in fear and anxiety, modification of amygdala function by pharmacological agents represents a likely mechanism of action as well as a target to guide future drug development. The evidence for amygdala involvement in anxiolytic action comes from both human imaging studies as well as work in animal models.

4.1. Human imaging studies: Effects of anxiolytics on amygdala activity and emotion

Given the highly complex and subjective nature of anxiolytic drug response in humans, neuroimaging represents an invaluable tool for drug evaluation and discovery.

Benzodiazepines: Benzodiazepines exert their anxiolytic action through binding to $GABA_A$ receptors, which leads to enhanced GABA activity and a subsequent increase in inhibitory tone. Despite the long history and current prevalence of benzodiazepine use for anxiety disorders [182,183], there is a paucity of human neuroimaging studies utilizing this class of drug, especially compared to those using antidepressants. This may have to do with eclipse of benzodiazepines by antidepressants as first line agents for many anxiety disorders [182].

Various studies have utilized healthy volunteers undergoing experimental challenges in an attempt to elucidate the neurobiology underlying the anxiolytic effect of benzodiazepines. These studies have found that benzodiazepines have the ability to impair functions related to amygdala activity including fear conditioning [184-186], recognition of fearful emotional faces [187], and memory for emotional stimuli relative to neutral stimuli [188,189].

Neuroimaging work appears to support a role for the amygdala in benzodiazepine action, although this may be dependent upon the nature of the accompanying neuropsychological challenge. Specifically, lorazepam was found to decrease amygdala activation during an emotional face assessment task without modifying baseline levels of anxiety or task recognition [190]. A similar finding was found with diazepam, which decreased amygdala response to fearful faces, and also impaired fearful face recognition [191]. However, during anticipation of aversive electrical stimulation, lorazepam failed to produce changes in amygdala activity [192]. Thus, while there is support for benzodiazepine induced modulation of the amygdala during processing of threatening/emotional stimuli, further studies are needed to clarify the neural correlates of benzodiazepine-induced anxiolysis.

β-Blockers: The β-blocker propranolol has a substantial history of being utilized to reduce somatic symptoms of fear and anxiety in situations such as stage fright [193] and acute panic [194-195]. More recently, research on the role of amygdala NE and β-receptors in facilitating emotional memory formation (see Table 4 and associated text) has caused much excitement and controversy about the use of propranolol to prevent PTSD [196-198]. Thus far, initial trials have demonstrated limited efficacy [199,200]. Despite lack of success in the application of propranolol to PTSD, neuroimaging studies in healthy human subjects have confirmed the ability of propranolol to modulate amygdala activation to emotional stimuli. Propranolol was found to decrease amygdala activation to emotional faces irrespective of emotional valence [201]. Furthermore, supporting a role for the amygdala NE in the encoding and consolidation of emotional stimuli, a separate study found that propranolol was able to decrease amygdala reactivity to emotional pictures of high valence as well as decrease the subject's memory for them [202].

Selective Serotonin Re-uptake Inhibitors: Antidepressant drugs, and selective serotonin re-uptake inhibitors (SSRIs) in particular, have become first line drugs for many of the anxiety disorders [182,203]. As such, there has been comparatively more work investigating these drugs in humans using advanced imaging techniques.

Most antidepressants are unique from benzodiazepines and β-blockers in that a time lag exists between initial treatment and onset of anxiolytic effects. In line with a potential anxiogenic role of serotonin in the amygdala (see Table 2 and associated text), some patients have reported an initial exacerbation of anxiety upon acute dosing of SSRIs [203]. In studies on healthy subjects, acute dosing of the SSRI citalopram can enhance recognition of fearful faces as well as increase emotion-potentiated startle response [204-206]. These effects are reversed when citalopram treatment is continued for 7 days [207,208].

Attempts to correlate the acute versus sub-chronic effects of SSRIs with neural activation have resulted in unexpected findings. On one hand, sub-chronic citalopram treatment was found to decrease amygdala activation to unconscious fearful stimuli [209], suggesting a relationship between repeated SSRI treatment, changes in emotional processing, and decreased amygdala activity. However, acute doses of citalopram have also been found to decrease amygdala activation to fearful faces [208,210,211]. Divergent effects of acute versus sub-chronic citalopram on emotional recognition but similar effects on amygdala response could suggest that the amygdala does not play a core role in acute SSRI-induced anxiety or chronic SSRI-induced anxiolysis. However, it has been emphasized that the effects of serotonergic challenge on fear recognition and amygdala activation appear to be dependent upon the individual's baseline sensitivity to threat [212], gender [213] and genotype [214]. Thus differences in subject profiles both between and within studies could have confounded results.

Overall, it appears that pharmacotheraputics commonly used to treat anxiety disorders may modulate amygdala function. In particular, it appears that anxiolytics can reduce amygdala reactivity to highly emotive or fearful stimuli. Given that amygdala hyper-reactivity to similar stimuli is the most common finding across all anxiety disorders (with the exception of adult GAD – see Section 2.2), it is possible that the anxiolytic effects of these drugs may be in part, mediated by dampening amygdala function.

4.2. Evidence delineating effects of anxiolytic drugs on amygdala function in animal models of anxiety states

Benzodiazepines: While benzodiazepine receptors exist throughout the brain, there is a particularly high density in amygdala regions [215,216]. There is much evidence from animal models to suggest that it is the action of benzodiazepines in the amygdala that mediates their anxiolytic effect. For example, early evidence demonstrated that local amygdala infusion of benzodiazepines produces anxiolytic-like effects in conflict models of anxiety [217-220]. These effects can be reversed by systemic [217,219] or direct amygdala administration of benzodiazepine antagonists [220]. Anti-conflict effects are most apparent when the benzodiazepines are injected into the BLA, and are absent when injected into the CeA [219,220]. While anti-conflict effects of benzodiazepines have been observed in the CeA, these were with substantially higher doses [221]. Further studies suggest that the BLA and not the CeA is essential for the anxiolytic effects of benzodiazepines in the EPM [149,222,223]. However, with regards to the shock probe burying test, it appears that the CeA is responsible for benzodiazepine-induced impairment of passive avoidance [223]. Although contradictory results exist on the role of benzodiazepines in the BLA versus CeA, particularly when animals are tested on the EPM [9,84,224] have suggested that distinct benzodiazepine receptor subtypes located within subregions of the amygdala may differentially alter avoidance responses to "potential threat" (EPM and BLA) versus "discrete, unambiguous threat" (shock probe burying and CeA).

As discussed in the human studies in Section 4.1 above [184,188,189], a key aspect of benzodiazepine action may be the ability to modulate emotional memory. Here the BLA once again appears to be a main site of benzodiazepine action. Lesions of the BLA, but not the CeA, block the benzodiazepine induced deficits in inhibitory avoidance memory [225,226]. Similar impairments were seen by direct injection of benzodiazepine into the BLA and not the CeA [227]. Enhancement of memory consolidation could be induced by BLA infusion of a benzodiazepine antagonist [228]. Given that individuals with anxiety disorders may be hypervigilant to cues associated with threatening stimuli and biased to form memories regarding such stimuli [229,230], the pro-amnestic effects of benzodiazepines in the BLA may represent a putative mechanism of action.

β-Blockers: The evaluation of β-blockers (with propranolol being the prototypical agent) in animal models has revolved mainly around their utility in models of memory and fear conditioning. Within the BLA, stress hormone elicited increases in norepinephrine have been found to enhance the consolidation of emotionally relevant memories [231,232]. This appears to be particularly true with contextual fear conditioning [178] and reconsolidation of fear memory following extinction [180,197,233; Table 4]. In particular, local infusions of propranolol are able to block reconsolidation of fear [180,233]. Recently, it has been demonstrated that β-adrenoreceptor activation within the BLA decreases surface expression of $GABA_A$ receptors, and this phenomenon is necessary for the reinstatement of fear following extinction [234]. It is proposed that propranolol, through blocking the decrease in $GABA_A$ receptor surface expression, prevents fear reinstatement by maintaining feed forward inhibition from BLA interneurons and thus dampening activity of BLA projections [234]. This finding is noteworthy as it suggests that hyperactive noradrenergic activity in PTSD [235,236] may lead to reduced $GABA_A$ availability, explaining a potential mechanism for the relative ineffectiveness of benzodiazepines in PTSD populations [237,238].

Despite the action of β-blockers within the amygdala to modulate fear conditioning (see Table 4), attempts at testing propranolol in other animal models of PTSD have met with mixed results, echoing the mixed efficacy seen thus far in humans [199,200,239,240]. One such model is exposure to predator odor in rodents, which produces long lasting increases in anxiety like behavior [241-243]. The increases in anxiety like behavior following exposure to predator odor is influenced by a long lasting potentiation in BLA activity [243], supporting the role of the amygdala in mediating the consequences of fear and trauma. Propranolol administered 1 minute following exposure to predator odor to rats blocks the development of anxiogenesis in various tests, including the EPM, one week later [241]. However, when propranolol administration is delayed to 1 hour following predator odor exposure, no effects are seen when rats are subsequently tested on the EPM 30 days later [242]. These results highlight once again a potential key role of timing if propranolol is to be effectively implemented in clinical patients. Similarly, findings that propranolol seems most effective in blocking the *re*consolidation of fearful memories [233, 180, 197] (also see Table 4) suggests that future work should be aimed at establishing protocols for the integration of propranolol during exposure therapy, in which extinction and reconsolidation processes are most active. Specifically, it would seem important that propranolol not be administered shortly after exposure therapy, as this might interfere reconsolidation processes within the amygdala. On the other hand, propranolol would likely have utility when PTSD patients encounter aversive stimuli outside the context of therapy which could potentially undermine the therapeutic process and lead to reinstatement.

Selective Serotonin Re-uptake Inhibitors: Similar to human studies, animal models of anxiety-like behavior demonstrate divergent behavioral effects of acute versus chronic SSRI administration. Increased anxiety-like behavior with acute treatment of SSRIs and its reversal with chronic treatment has been found in novelty-suppressed feeding [244], EPM testing [245,246], and the social interaction test [247]. While a large percentage of studies reveal acute anxiogenic effects and chronic anxiolytic effect, there are exceptions (for review, see [248]).

Much evidence suggests that enhanced activity at $5\text{-}HT_{2C}$ within the BLA by SSRIs produces acute anxiogenic effects, while the eventual downregulation of these receptors by chronic treatment leads to eventual anxiolysis. For example, amygdala or BLA $5\text{-}HT_{2C}$ receptors have been found to produce anxiety-like responses in a variety of tests [249,250] (see Table 2). Blockade of $5\text{-}HT_{2C}$ receptors within the BLA prevents the acute anxiogenic effect of the

SSRI fluoxetine on the Vogel conflict test [251]. Systemic 5-HT_{2C} antagonism also prevents the increase in fear conditioning [252], decrease in social interaction [247,253], and escape response to airjet [254] following acute SSRI treatment. Following chronic treatment with SSRIs, 5-HT_{2C} agonists have attenuated anxiogenic effects on the exacerbation of OCD symptoms in humans [255,256], on social interaction [257] and hyperlocomotion [258], suggesting down-regulation of the ability to 5-HT_{2C} receptors in the amygdala to produce anxiogenic responses following chronic SSRI treatment. Thus, the amygdala (BLA in particular) may be an important locus of action for the long-term effects of SSRIs on anxiety.

4.3. Future potential anxiolytic targets

The literature reviewed above suggests that in part, the effects of anxiolytic drugs may be mediated by altering amygdala function – either global dampening of the amygdala by benzodiazepines, or specific actions on 5-HT and NE receptors within particular amygdala subregions. However, to improve therapeutic efficacy and reduce relapse, several aspects of amygdala pharmacology discussed above might provide useful potential anxiolytic targets in the future.

Findings suggesting down-regulation of anxiogenic 5-HT_{2C} receptors in the amygdala following chronic SSRI treatment (Section 4.2.) present a potential strategy of reducing onset latency of SSRIs as well as enhancing their effects. Specifically, blocking 5-HT_{2C} receptors at the initiation of SSRI treatment would be expected to produce a faster onset of anxiolytic action. Currently, there are no selective 5-HT_{2C} antagonists available for human use. However, atypical antipsychotics [259] as well as atypical antidepressants such as mirtazapine [260] possess 5-HT_{2C} antagonist activity. While there is evidence that antipsychotic augmentation of SSRIs may improve anxiolytic efficacy, their use has been limited by poor tolerability [for review see 261]. Although research is lacking, mirtazapine and the melatonin receptor agonist/5-HT_{2C} receptor antagonist agomelatine [262] may provide the advantage of targeting anxiogenic 5-HT_{2C} in the amygdala with less side effects.

Furthermore, the recent observation that β-adrenoreceptor activation within the BLA results in decreased of $GABA_A$ receptor surface expression necessary for fear reinstatement [234] (and see Section 4.2.) suggests that the combination of propranolol and a benzodiazepine may have unique benefit for PTSD. By blocking β-adrenoreceptors with propranolol, one might be able to enhance benzodiazepine receptor availability, and increase benzodiazepine-induced inhibition of fear circuits within the amygdala. While currently speculative, the use of propranolol to enhance benzodiazepine action in the amygdala may represent a potential creative treatment strategy in a population that is traditionally refractory to benzodiazepine treatment.

While current pharmacotherapeutic strategies for the treatment of anxiety disorders target monoamine function, this has predominantly been related to altering 5-HT or NE levels or receptor activity [8]. However, Table 3 clearly shows a role for DA in the amygdala in mediating both fear and anxiety, and the role for DA and both D_1 and D_2 receptors in acquisition and retention of conditioned fear in particular appears quite robust. Thus, reducing DA function might serve as means by which to treat anxiety disorders in which fear plays a major component. The obvious disadvantage of dopaminergic-based pharmacotheraputics is potential for major cognitive and motoric side-effects, limiting the treatment options with the currently available dopaminergic agents. Atypical antipsychotic drugs incorporate DA receptor blocking activity while avoiding many of the motoric and cognitive issues of traditional agents. There is evidence that atypical agents possess anxiolytic activity [261], but metabolic side effects make them poorly tolerated. Furthermore, because atypical antipsychotics also have high affinity for 5-HT receptors, the contribution of DA modulation to their anxiolytic effects in humans is currently unknown. One potential strategy may be the use of partial agonists to reduce DA activity in the amygdala via activation of inhibitory presynaptic D_2 autoreceptors. While non-selective for DA, the D_2 partial agonist aripiprazole has demonstrated anxiolytic efficacy similar to other atypical antipsychotic drugs [263]. In the future, more selective DA partial agonists may have additional benefit without unwanted side-effects.

Finally, CRF has been identified as an important neuropeptide in the regulation of monoaminergic activity in the amygdala in response to anxiogenic or fearful stimuli (Section 3.2). Furthermore, CRF and its receptors (CRF_1 and CRF_2) are implicated in fear and anxiety within animal models and in the development of anxiety disorders [12,121-129]. Upon the development of non-peptide CRF_1 receptor antagonists that cross the blood-brain barrier, there was great interest in the use of CRF_1 receptor antagonist in the treatment of anxiety disorders. To date, there have been limited phase II clinical trials published regarding the use of CRF_1 receptor antagonists in anxiety disorders [264]. Of those, preliminary findings suggest the CRF_1 receptor antagonist-treated groups did not differ from placebo-treated groups in anxiety symptomology in both social anxiety disorder and GAD [264]. However, it has been suggested that efficacious concentrations have not been established for the various CRF_1 receptor antagonists, and it is clear that further clinical trials are necessary. One potential promising area in the treatment of anxiety disorders may actually lie in CRF_2 receptor antagonists. As outlined in Section 3.2, CRF_2 receptors mediate 5-HT activity in the amygdala, are up-regulated in animal models of anxiety, and an antagonist of this receptor reduces heightened anxiety in rats [11,12,127,128,131,132,137). The challenge lies in developing non-peptide CRF_2 receptor antagonists that cross the blood-brain barrier, so that the efficacy of such ligands can be determined for anxiety disorders.

5. Conclusion

Human imaging studies in non-patient populations suggest amygdala activation in response to fearful stimuli, and that the magnitude of this response is positively correlated with trait anxiety. Furthermore, individuals suffering from an anxiety disorder (with the possible exception of adult GAD) show exaggerated amygdala responses to fearful or emotive stimuli, which again is positively correlated with the severity of symptoms. Moreover, reactivity of the amygdala to fearful stimuli is reduced by anxiolytic drugs in healthy subjects, and long-term pharmacotherapy or CBT reduces amygdala hyper-reactivity in anxiety disorders. Animal studies corroborate an important role for the amygdala in fear and anxiety, with specific subregions mediating acquisition and expression of fear, fear memories and anxiety, and the monoamines within each of these regions often playing a very specific role in facilitating or attenuating fear or anxiety. Both human and animal studies suggest dysfunction of the amygdala might arise in part, from inadequate top-down control by regions such as the medial prefrontal cortex, and in part, from altered neuropeptide regulation of amygdala monoaminergic systems. Overall, the amygdala plays a critical role in anxiety disorders, and understanding the function of this region in fear and anxiety states and how dysfunction of the amygdala results in anxiety disorders is critical to improving long-term treatment outcomes.

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