

## MIT Open Access Articles

### *Resolving the neural circuits of anxiety*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

**Citation:** Calhoun, Gwendolyn G. and Kay M. Tye. "Resolving the neural circuits of anxiety." Nature Neuroscience 18:10 (October 2015), pp. 1394-1404.

**As Published:** <http://dx.doi.org/10.1038/nn.4101>

**Publisher:** Nature Publishing Group

**Persistent URL:** <http://hdl.handle.net/1721.1/102969>

**Version:** Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

**Terms of use:** Creative Commons Attribution-Noncommercial-Share Alike



# Resolving the Neural Circuits of Anxiety

Gwendolyn G. Calhoun<sup>1</sup> and Kay M. Tye<sup>1,2</sup>

<sup>1</sup>The Picower Institute for Learning and Memory, Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

<sup>2</sup>To Whom Correspondence Should be Addressed:

Kay M. Tye, PhD

Picower Institute for Learning and Memory

Department of Brain and Cognitive Sciences

77 Massachusetts Ave, Bldg-Rm 46-6263

Massachusetts Institute of Technology, Cambridge, MA 01239.

[kaytye@mit.edu](mailto:kaytye@mit.edu)

**Abstract**

Although anxiety disorders represent a major societal problem demanding new therapeutic targets, these efforts have languished in the absence of a mechanistic understanding of this subjective emotional state. While it is impossible to know with absolute certainty the subjective experience of a rodent, rodent models hold promise in dissecting well-conserved limbic circuits. The application of modern approaches in neuroscience has already begun to unmask the neural circuit intricacies underlying anxiety by allowing direct examination of hypotheses drawn from existing psychological concepts. This information points toward an updated conceptual model for what neural circuit perturbations could give rise to pathological anxiety, and thereby provides a roadmap for future therapeutic development.

## Introduction

In health, the neural systems that underpin emotion dynamically integrate internal states and external stimuli to enable the rapid selection of situationally appropriate behaviors. The function of highly reciprocal limbic circuits is to integrate the barrage of signals received by an individual, including motivational drives<sup>1</sup>, environmental context, and learned associations based upon past events, and to consolidate them into a singular gestalt experience *which is emotional in quality and directs the behavioral response*.

That emotions invigorate behaviors which aid in survival is an idea with a long history. In *The Expression of the Emotions in Man and Animals*, Darwin conjectured that emotions evolved as a result of natural selection<sup>2</sup>, and consistent with this evolutionary provenance, emotional behaviors can be observed across species. Whether animals experience emotions as humans do is a matter of controversy<sup>3,4</sup>; however, as Anderson and Adolphs argue in their 2014 review, “primitive emotion states are expressed by externally observable behaviors” across species, allowing the objective study of these states and the neural systems that drive them in model organisms<sup>5</sup>.

Here, we review the current state of our field and postulate that anxiety disorders arise from disruptions within the highly interconnected circuits normally serving to process the stream of stimuli detected by our brains from the outside world. We propose that information processing within distributed, interlinked nodes results in the assignment of emotional value to environmental stimuli, operationalized here as “interpretation,” as well as the weighting of potential threats against previously learned associations and competing motivational needs, referred to here as “evaluation.” Moreover, we suggest that computations within corticolimbic circuits resulting in the interpretation of environmental threat subsequently drive an observable anxiety-like response. Finally, we posit that perturbations anywhere within these circuits disrupts balance within the entire system, resulting in a fundamental misinterpretation of neutral sensory information as threatening, and leading to inappropriate emotional – and thereby behavioral – responses seen in anxiety disorders as well as other psychiatric disease states.

## **Anxiety Disorders: Too Much of a Normal Thing**

Anxiety represents a state of high arousal and negative valence<sup>6</sup>, and results in enhanced vigilance in the absence of an immediate threat<sup>7</sup>. Occasional anxiety is a normal aspect of the emotional repertoire, and aids survival by increasing awareness and enabling rapid responses to possible hazards. Anxiety is characterized by subjective experiences such as tension and worried thoughts, as well as physiological changes including sweating, dizziness, and increases in blood pressure and heart rate. This emotional state can be triggered by stimuli that do not pose immediate danger, or can be internally generated. By contrast, the related emotional state of fear occurs acutely in response to a real or perceived imminent threat, and dissipates rapidly upon removal of the eliciting stimulus<sup>7</sup>.

Although healthy individuals experience sporadic bouts of anxiety, anxiety that is persistent, disruptive, or disproportionate to actual danger can be debilitating and is considered pathological. The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) divides pathological anxiety into three main categories of disorders, including obsessive – compulsive and related disorders, trauma- and stressor-related disorders, and anxiety disorders<sup>8</sup>. The precipitating stimuli differ among these diagnoses, however in all cases, the somatic, cognitive, and behavioral manifestations of anxiety interfere with normal functioning and lead to substantial economic and personal burdens<sup>9–11</sup>.

The prevalence of anxiety disorders is estimated to be 18% among adults<sup>12</sup> with a *lifetime prevalence* of more than 28%<sup>13</sup> (see call-out box, below), however a considerable portion of pathologically anxious individuals do not receive adequate treatment<sup>14</sup>. Despite the pervasiveness of anxiety disorders, relatively few novel therapeutic targets have been identified for the treatment of anxiety (for review of pharmacotherapeutic strategies for the treatment of anxiety, see<sup>15–17</sup>). Since the 1950s, new molecular entities approved by the FDA with primary indications for anxiety have been limited to benzodiazepines (BZDs) and the atypical anxiolytics buspirone, meprobamate, and hydroxyzine pamoate<sup>18</sup>. More recently, the label indications for antidepressants such as certain tricyclic antidepressants, selective serotonin reuptake inhibitors (SSRIs), and serotonin norepinephrine reuptake inhibitors (SNRIs) have been extended by the FDA to include anxiety<sup>19</sup>. Despite these additions, the therapeutic arsenal for anxiety disorders remains inadequate; the available drugs do not successfully relieve anxiety in all patients, and unwanted side effects reduce compliance among those for whom they do. By comparison, novel drug development for the treatment of hypertension has remained steady over the same time period<sup>18</sup> (Figure 1).

In order to improve treatment strategies for anxiety, a thorough understanding of the neural circuits governing this emotional state in health and disorder is needed<sup>20</sup>.

### **Measuring Anxiety-Related Behaviors in Rodents**

For a truly mechanistic understanding of the neural underpinnings of anxiety, the ability to manipulate specific circuit components is required, demanding the use of next-generation technologies in model organisms<sup>21</sup>. In order to provide useful insights about the pathophysiology of anxiety disorders, measurements of anxiety-like behaviors in animals must meet the essential criterion of validity (see call-out box)<sup>22,23</sup>. Despite the inherent challenges of using model organisms to study the neural substrates of anxiety disorders, a diverse array of strategies for assessing externally observable anxiety-related phenotypes in animals has been developed<sup>5</sup>.

Rodents are well suited to this purpose and have historically been used in basic research and drug development to model fear learning, stress, and anxiety. In this review, we focus on discussion of “state” anxiety, defined as a behavioral state of enhanced arousal and vigilance in response to uncertain situations<sup>24</sup>. This classification refers to anxiety evoked by potentially hazardous situations<sup>25</sup>, rather than the pathological “trait” anxiety of the clinical literature, wherein anxiety is a persistent, non-adaptive attribute, which leads individuals to overestimate potential dangers in conditions of ambiguity<sup>24</sup>. This contrast notwithstanding, the neural systems implicated in anxiety by rodent studies are consistent with those identified in human patients<sup>26-34</sup>, underscoring the utility and translatability of these rodent studies. Tests of fear and anxiety in rodents have been reviewed extensively elsewhere<sup>22,23,25</sup>, however we offer here a brief description of commonly used strategies for measuring anxiety-like behaviors in mice (summarized in Figure 2).

The majority of anxiety assays adapted for mice are ethologically based. These tasks capitalize upon the innate, conflicting drives of rodents to explore novel spaces and to avoid open, exposed, and brightly illuminated areas where they might be more vulnerable to environmental threats. Generally in these approach-avoidance conflict tasks, mice with an anxious phenotype tend to spend more time in enclosed or “safe” zones of the behavioral apparatus than controls. In the elevated plus maze (EPM), anxious mice avoid the open arms of the maze in favor of the walled arms<sup>35</sup>. The ambiguous center of the EPM is eliminated in the elevated zero-maze, however the task resembles the EPM otherwise in that anxious mice prefer the walled quadrants to the open ones<sup>36</sup>. In the open field test (OFT), anxious animals remain along the edges of the enclosure<sup>37</sup>, whereas in the light-dark box, anxiety-related behavior is

measured as a propensity to remain in the darkened portion of the chamber<sup>38</sup>. Other less commonly used ethological tests include the staircase task<sup>39</sup>, in which anxious mice tend to rear more and climb fewer steps, the elevated alley<sup>40</sup>, in which mice must traverse a partially illuminated rod, and the hole board<sup>41</sup>, in which animals can forage in holes along the floor of the otherwise exposed apparatus.

These approach-avoidance assays are appealing for a number of reasons. They have a high degree of face validity, in that most of the anxiety disorders include a component of avoidance of a potentially hazardous stimulus. Furthermore, anxiety-like behaviors in these tasks are reduced by anxiolytic drugs, particularly BZDs<sup>42</sup>. Finally, limited training is required for animals to perform them, rendering this group of anxiety assays high throughput. An important caveat of these tasks, however, is that they are sensitive to overall changes in locomotion, so the use of control tests for motor deficits is necessary when employing these measures to assess anxiety-like behavior.

A further confound of exploration-based tasks is that they cannot distinguish a reduced anxiety phenotype from increased novelty-seeking, exploration, or impulsive approach behavior<sup>23</sup>. A number of alternative tasks for assessing anxiety-related behaviors in mice avoid this drawback; for instance, in active-avoidance tasks, mice direct their energies toward minimizing threatening stimuli. Rodents will bury an electrified probe following conditioning in which they receive shocks from the probe<sup>43</sup>, and will even spontaneously bury novel marbles introduced into their home cages<sup>44</sup>. This burying behavior is quantifiable and sensitive to anxiolytics<sup>45,46</sup>. Hyponeophagia (novelty suppressed feeding) has also been used to assess anxiety-like behavior in rodents; in a novel environment, hungry mice exhibit an increased latency to feed that is sensitive to BZDs and SSRIs<sup>47,48</sup>.

Anxiety phenotypes are also assessed using measures based upon rodent social interactions. Rodents produce and detect ultrasonic vocalizations (USVs) as a means of communication, and the frequency of these vocalizations varies relative to the apparent emotional state of the animal<sup>49</sup>. When removed from their mothers, pups emit USVs in the frequency range associated with fear and anxiety-like responses, and such stress-induced vocalizations are reduced by anxiolytics<sup>50</sup>. In the social interaction task, social contacts between unfamiliar individuals in a brightly illuminated arena are quantified; anxiolytics have been found to increase social interaction in this task<sup>51</sup>.

Complementary to the behavioral assays, physiological measures of vital signs and circulating levels of stress hormones provide an additional indicator of anxiety-like phenotypes in mice. Although these types of measures are more commonly collected in order to quantify

stress, their use in the assessment of anxiety in rodents has its basis in the strong somatic components of clinical anxiety<sup>8</sup>. Moreover, a thorough understanding of the neural circuits underlying anxiety must include a consideration of its somatic symptoms, as changes in heart rate, respiration, and glucocorticoid levels require the activation of distinct pathways from those that drive anxiety-like behaviors<sup>31,52</sup>. Similarly, paradigms traditionally used to study fear, such as auditory fear conditioning – in which auditory cues (conditioned stimuli, CS) predict delivery of footshocks (unconditioned stimuli, US) – and the innate acoustic startle response to unexpected bursts of high decibel noise, are often used to interrogate anxiety circuits and to draw inferences about how fear learning may be disrupted in anxiety disorders<sup>53</sup>.

Recent technological advances have been instrumental in advancing our understanding of the neural substrates of anxiety measured in these behavioral assays. For example, the use of optogenetics to manipulate behaviors within these behavioral paradigms has been central in establishing causal relationships between the activity of neural circuits and anxiety. Such nascent strategies have catapulted preclinical neuroscience research into a new era of circuit-level investigations. We focus here upon insights gained as a result of this circuit-level approach, which is rapidly becoming the mainstay of the current era of neuroscience research.

### **Neural Pathways of Fear and Anxiety**

For more than a century following the original discovery that temporal lobe structures govern emotional behaviors<sup>54</sup>, our understanding of the neural substrates of anxiety was largely restricted to insights gleaned through lesion and inactivation studies. While this early work importantly led to the identification of key loci controlling anxiety, notably including the amygdala, the bed nucleus of the stria terminalis (BNST), the ventral hippocampus (vHPC), and the prefrontal cortex (PFC), progress in dissecting the contribution of regional microcircuits to this emotional state was limited. Moreover, the impact of changes within individual structures upon activity in distal projection targets, or how such changes may functionally result in anxiety, remained elusive. Novel approaches in animal research, especially targeted manipulations of neurons based on projection target or genetic identity via optogenetics, have opened these questions for causal testing and accelerated the pace of discovery. The resulting paradigm shift in anxiety research has expanded the focus to broader circuit-level interactions in emotional processing, such that it is now clear that anxiety requires the recruitment of a distributed array of interlinked neural circuits. Here, we discuss the contribution of individual nodes in the context of larger circuit relationships that have been unveiled as a result of recent technological advances, and reconcile region-specific studies of anxiety into a broader circuit-level network.



### ***Interpreting Threats on the Macrocircuit Level***

To assess a situation as threatening and render an anxiety-like response, an individual must first detect environmental stimuli through the sensory systems and then identify them as aversive or potentially dangerous. Coordinated activity within the amygdala, BNST, vHPC, and PFC enables such *interpretation* of threat in the environment. These structures are highly interconnected, with multiple reciprocal projections facilitating macrocircuit-level interactions, which subsequently initiate vigilance and defensive behaviors through the recruitment of brainstem and hypothalamic nuclei. In this macrocircuit, sensory information regarding potential threats flows along circular loops in which it is transmitted both forward (from the amygdala onward to the BNST, vHPC, and mPFC, and consequently to downstream effector nuclei) and backward (from the mPFC and vHPC back to the amygdala and BNST). Threats are detected and interpreted as worthy of enhanced vigilance in the former, and this initial interpretation is evaluated in the latter.

A major determinant of whether environmental stimuli are interpreted as threatening occurs within the amygdala, wherein sensory stimuli are imbued with emotional value. As the major input nucleus in the amygdala, the BLA (containing the lateral (LA), basal (BA), and basomedial (BM) sections) receives excitatory afferents regarding sensory stimuli from the thalamus and sensory cortices<sup>55</sup>. Processing of this sensory information within the BLA results in the formation of associations between neutral predictive stimuli and outcomes of positive or negative valence<sup>56</sup> via Hebbian mechanisms<sup>57-59</sup>. In this way, cues predicting threat are themselves recognized as threatening<sup>60</sup>, and likewise, those predicting reward themselves become rewarding<sup>61,62</sup>.

The emotional valence of these cues then determines whether canonical fear or reward pathways are recruited downstream of the BLA<sup>63</sup>; in fear or anxiety provoking circumstances, projections from the BLA targeting the central amygdala (CeA, containing the lateral (CeL) and medial (CeM) subdivisions)<sup>53,64</sup> and the BNST<sup>31,65</sup> are activated. The activity of BLA neurons is not exclusively shaped by sensory input, however; principal neurons and interneurons in the BLA have been shown to receive monosynaptic input from mPFC and vHPC, and send reciprocal projections to both of these regions<sup>66-68</sup>. Activity within these pathways can both directly invigorate the anxiety response (e.g., through projections of the vHPC to the lateral septum and hypothalamic nuclei; see below), as well as influence the likelihood of a threat

appraisal (e.g., through fear memory retrieval via mPFC projections to the amygdala; see below, and<sup>69</sup>).

### ***Microcircuits and Interactions among Nodes***

Within this larger macrocircuit, individual nodes process information via local pathways. The advent of optogenetics is allowing in-depth interrogation of these microcircuits, to enhance our understanding of the mechanisms whereby genetically- or projection target- defined populations of cells shape the processing within and among the amygdala, BNST, vHPC, and mPFC.

These modern technologies have enabled detailed elaboration upon the canonical amygdala microcircuit mediating fear learning. Briefly, activation of LA neurons induces unconditioned freezing<sup>70</sup>. These cells develop robust responses to shock-predictive cues, corresponding to freezing behavior when the cues are presented<sup>71</sup>. The presence of an unambiguous threat such as footshock results in rapid fear responses by engaging microcircuits within the CeA. Within this circuit, glutamatergic signals from the BLA are conducted onward to the CeL, where they impinge upon two populations of mutually inhibitory GABAergic neurons, the protein kinase C delta (PKC $\delta$ )-negative/CeL<sub>ON</sub> cells and the PKC $\delta$ -positive/CeL<sub>OFF</sub> cells<sup>72,73</sup>. Inhibition of the latter population by the former results in the disinhibition of CeM output neurons, consequently driving freezing behavior and changes in heart rate via CeM projections to the periaqueductal gray (PAG) and dorsal vagal complex (DVC), respectively<sup>52</sup> (Figure 3). Consistent with the apparent role of PKC $\delta$ -positive neurons in gating fear responses, direct activation of these cells produces an anxiolytic effect on the EPM, OFT and light-dark box<sup>74</sup>. Activation of somatostatin (SOM) positive CeL neurons by the LA<sup>75</sup> and paraventricular nucleus of the thalamus (PVT)<sup>76,77</sup> has also been shown to drive fear learning through an overall increase in inhibition within the CeL. Furthermore, a population of cells within the BLA projecting directly to the CeM shows evidence of potentiation following fear conditioning, and photoinhibition of these neurons inhibits the acquisition of the fear association<sup>63</sup>. For more detailed consideration of the microcircuits driving fear learning, see<sup>53,78</sup>.

In the absence of immediate threat, anxiety-like behaviors can arise from recruitment of these same amygdala pathways. For instance, activity within certain populations of BLA neurons promotes anxiety phenotypes in ethological assays. Tonic activity in a subset of BLA neurons has been shown to track with anxiety-like behavior in the EPM and OFT<sup>79</sup>. Moreover, photoactivation of BLA somata increases measures of innate anxiety<sup>33</sup> as well as learned inhibitory avoidance<sup>80</sup>. Targeted photostimulation of BLA inputs to CeL, by contrast, is

anxiolytic, presumably via enhanced inhibition over CeM projection neurons<sup>33</sup>. This work demonstrates the importance of projection-defined interrogation of these circuits, as individual projection neurons within the same region can enact opposing behavioral effects depending on their efferent targets.

Initiation of fear and sustained anxiety responses requires the recruitment of the BNST<sup>7</sup>, which occurs partly as a result of direct innervation by BLA afferents, as well as through dense glutamatergic input from the HPC<sup>81,82</sup>, the mPFC, the entorhinal cortex, and insular cortex<sup>55,83</sup>. Some redundancy of amygdala and BNST function ensures that fear learning remains intact in the face of localized damage or dysfunction. For example, in the absence of a functional BLA, the BNST acts as a compensatory site in the acquisition of fear memories, although this BLA-independent fear learning requires additional training<sup>84</sup>. Moreover, individual subregions of the BNST have been shown to differentially regulate separable features of the anxiety phenotype<sup>31,85</sup> (Figure 3). BLA inputs to the anterodorsal BNST (adBNST) promote behavioral and physiological anxiolysis, however local inhibition of adBNST by the oval nucleus of the BNST (ovBNST) is anxiogenic<sup>31</sup>. These effects upon the innate anxiety state are mediated via adBNST projections to the ventral tegmental area (VTA), lateral hypothalamus (LH), and the parabrachial nucleus (PB), which independently regulate subjective preference, risk avoidance in the EPM and OFT, and respiration rate, respectively<sup>31</sup>. BLA inputs to the ventrolateral BNST (vlBNST) promote freezing during uncontrollable stress and subsequent reduction in social interaction, both of which responses are reduced by inhibition of vlBNST<sup>86</sup>. The ventral BNST (vBNST) also regulates anxiety through its innervation of the VTA; activity in glutamatergic vBNST neurons projecting to the VTA produces anxiety-like behaviors, whereas GABAergic neurons in the vBNST exert anxiolysis via a parallel pathway<sup>85</sup>.

Reciprocal interactions between the BLA and the vHPC have also been shown to regulate fear learning and anxiety-like behaviors. The HPC is a highly structured brain region, with an elaborated internal microcircuit, which has been reviewed in detail elsewhere<sup>87,88 89</sup>. BLA inputs to the vHPC promote anxiety-like behavior; for example, BLA projections to the hippocampal formation through the entorhinal cortex are necessary for the acquisition of contextual fear memories, as photoinhibition of these terminals during learning blocks freezing during context re-exposure<sup>90</sup>. Furthermore, glutamatergic terminals of BLA fibers onto CA1 pyramidal neurons in the vHPC bidirectionally control innate anxiety-related behaviors in the EPM and OFT<sup>66</sup>, such that increased activity in this projection enhances anxiety-like behavior and inactivation of this pathway reduces anxiety-like behavior<sup>27,66</sup>. These targeted investigations of BLA input to vHPC suggest that increased activation of cells in this region

produce anxiety-like behavior, however direct photostimulation of ventral DG granule cells has been found to *suppress* anxiety-like behaviors in the EPM and OFT<sup>91</sup>. Although these findings appear to conflict with those obtained through manipulation of BLA inputs to the vHPC, they can potentially be reconciled, as the low frequency stimulation of ventral DG used by Kheirbek and colleagues has been previously demonstrated to result in feed-forward inhibition of CA3 pyramidal cells<sup>92</sup>.

The effects of vHPC activation upon anxiety-related behaviors occur partially through its connections to the lateral septum (LS)<sup>93</sup>, which in turn is reciprocally connected to the hypothalamus<sup>94</sup>. Ipsilateral projections from vHPC to LS convey an anxiety signal; bilateral blockade of activity in either structure using muscimol increases open arm exploration in the EPM, as does disconnection of the two using pharmacological inactivation of vHPC in one hemisphere and concurrent inactivation of the contralateral LS<sup>95</sup>. Corticotropin releasing factor receptor (CRFR) activation in the LS increases anxiety-related phenotypes<sup>96</sup> by way of activation of CRFR type 2 expressing GABAergic projection neurons residing there<sup>97</sup>. Activation of these neurons results in inhibition of cells in the anterior hypothalamic area (AHA), which themselves inhibit the paraventricular nucleus of the hypothalamus (PVH) and PAG. The resultant disinhibition of these regions promotes neuroendocrine and behavioral aspects of the persistent anxiety state<sup>97</sup>, which redouble the complimentary actions of CeA and BNST activation.

In addition to producing anxiety-like behaviors via projections to the LS, the vHPC supports the interpretation of a given situation as threatening through its reciprocal connection with the BLA as well as its efferent projections to the mPFC. The vHPC importantly serves as a source of synchrony between the amygdala and mPFC during threatening situations (discussed in detail below). Furthermore, the vHPC specifically targets fear-encoding neurons within the BA (which themselves project to the mPFC), and the activation of these cells is necessary for fear renewal after extinction<sup>67</sup>. Neighboring cells in the BA that are innervated by PFC afferents fire in response to conditioned stimuli that have been extinguished, and project reciprocally to the PFC<sup>67</sup>.

### ***Evaluation of Threat: Regulation of Interpretation***

Naturalistic environments are often characterized by ambiguity, and the absolute absence of potential danger is rarely assured. In psychology, it has been proposed that there is an evaluative system that guides subsequent modulation of emotion in a regulatory fashion<sup>98</sup>. To prevent unchecked activation of pro-anxiety circuits, an additional layer of processing is

required to *evaluate* whether interpretations of environmental threats are accurate and weighted appropriately given internal (e.g. homeostatic, hormonal) or external (e.g. support of the conspecific group, extent of perceived danger) conditions. Such an evaluative system could provide permissive or restrictive feedback to interpretation circuits in order to promote or suppress the expression of anxiety-like behaviors.

An integral source of evaluation of threat interpretations is the mPFC, which regulates subcortical responses to threatening stimuli. As a neocortical structure, the mPFC is organized into six layers (I – VI) containing a majority of excitatory pyramidal neurons and a diverse array of inhibitory interneurons<sup>99</sup>. The mPFC can be parsed into distinct subregions based upon their cytoarchitecture, which are consistent with divergent functions among these regions<sup>100</sup>. The primary subdivisions of the mPFC in rodents include the prelimbic (PL) and infralimbic (IL) cortices. These receive inputs from midline thalamic nuclei, the BLA, and the HPC, and send reciprocal projections to BLA, as well as efferent projections to the striatum<sup>101</sup>.

Reciprocal connections between the mPFC and the amygdala have been extensively studied in the learned fear response as well as in anxiety disorders in both humans<sup>102,103</sup> and rodents, which we explore in depth below. The evaluative role of the PFC is demonstrated in this exemplar circuit, as PFC interactions with the BLA differ depending upon the degree of environmental threat. Correlated activity between the dorsal anterior cingulate region of the PFC and BLA underlies acquisition of aversive memories, and maintenance of such cross-regional correlations promotes resistance to extinction of fear memories<sup>104</sup>. During auditory fear conditioning, activity in BA neurons projecting to the PL is increased<sup>105</sup>, and PL responses to shock-predicting cues are increased after learning<sup>106</sup>. This increase in PL activation is likely due in part to phasic inhibition of local parvalbumin positive interneurons, which is necessary for cue-induced freezing behavior<sup>107</sup>. By contrast, extinction of the learned fear association increases activity in BA neurons targeting the IL<sup>105</sup>. Fittingly, increased activity in the IL is associated with fear extinction<sup>108</sup> (but see also<sup>109–111</sup>), and electrical stimulation of IL reduces freezing to the CS, even in animals that are resistant to extinction training<sup>108,112</sup>. In naïve mice, both of these subdivisions of mPFC exert similar levels of excitation and feed-forward inhibition upon BLA principal neurons. Following auditory fear conditioning, however, excitatory responses evoked by PL inputs in the BLA are increased as a result of enhanced AMPA receptor function<sup>113</sup>. Furthermore, PL activation of amygdalar subregions is necessary for retrieval of fear memories. Direct activation of the BLA by PL inputs mediates freezing responses to CS presentations within six hours of auditory fear conditioning, however, fear memory retrieval greater than 24 hours following conditioning necessitates PL recruitment of

PVT inputs to CeL<sup>114</sup>. For a more in-depth consideration of how interactions between the amygdala and mPFC impact fear learning, readers are directed to<sup>115</sup>. Taken together, these findings indicate that PL inputs to the amygdala facilitate responses to threatening stimuli, whereas IL inputs to the amygdala suppress them.

The distinct pathways engaged by the mPFC in conditions of high and low threat represent a mechanism whereby this region may dynamically permit or prevent anxiogenic activity in interpretation circuits. Additionally, the mPFC has been demonstrated to exert powerful feed-forward inhibition over the baseline activity of BLA principal neurons *in vivo* (<sup>116</sup>, but see<sup>117</sup>), and also to suppress LA responses to conditioned aversive stimuli<sup>118</sup>. Such inhibitory control enables the mPFC to trump threat interpretations in conditions of acceptably low risk in favor of engaging in appetitive behaviors. Moreover, the mPFC is ideally poised to orchestrate shifts between anxiety-like and reward-motivated behaviors, as it sends projections both to the amygdala and nucleus accumbens (NAc). mPFC efferents to the latter affect information processing within striatal projection neurons<sup>119</sup>, and stimulation of this pathway is reinforcing<sup>120</sup>.

Habituation can also suppress threat interpretations. As opposed to extinction, in which responses to a learned CS are diminished over time as a result of multiple unpaired presentations, habituation occurs when evoked behavioral responses are diminished following repeated presentations of a neutral or unconditioned stimulus<sup>121</sup>. This process is especially relevant to anxiolysis in the case of stimuli which are ambiguously threatening, such as police sirens in a busy neighborhood; although these stimuli may portend danger initially, over multiple exposures, they no longer evoke an anxiety response. The neural mechanisms of habituation have long been suggested to involve reduced transmission in stimulus-response pathways following repeated presentation of the stimulus<sup>122</sup>.

Energy homeostasis and motivation signals also shape the degree to which threat interpretations govern behavioral responses. Given sufficient motivation to seek food, to drink, or to mate, an animal will engage in these appetitive behaviors despite the presence of potential dangers. The comparison of apparent risks or costs to possible reward is a computation performed by circuits supporting motivated behavior, critically including the NAc and the mesocorticolimbic dopamine system (reviewed in depth elsewhere<sup>123–125</sup>). In cases in which expected benefits outweigh perceived costs, the impact of threat interpretations upon behavior is diminished. Hypothalamic drives to maintain homeostasis (i.e., to seek and consume food or water<sup>126,127</sup>) can also overwhelm threat avoidance and anxiety-like behaviors. Stimulation of lateral hypothalamic terminals in the VTA, for example, promotes sucrose seeking, even when

mice must cross an electrified floor to obtain the sucrose reward<sup>128</sup>. Thus, subcortical motivational systems contribute to the evaluation of threat interpretations by shifting the balance toward appetitive behaviors and away from anxiety-like behaviors.

### ***Synchrony between Interpretation and Evaluation Circuits***

The combined actions of distributed neural circuits emerging from the amygdala, BNST, vHPC, and mPFC result in the interpretation and evaluation of the emotional value of environmental stimuli. If such stimuli are identified as threatening based upon this assessment, anxiety-like behaviors may result. However, coordinated processing of potentially threatening stimuli must occur in order to elicit a well-defined behavioral response. Synchronization of local field potentials provides a mechanism whereby the timing of activity within these distributed regions could be orchestrated.

Interactions among the “emotional triad” (a term coined by Dr. Joshua Gordon, Columbia University), including BLA, mPFC, and HPC, are shaped by dynamic changes in the degree of synchrony in the local field potential (LFP) oscillations of these regions. Theta activity (4 – 12 Hz) in the vHPC is associated with anxiety-like behavior in rodents<sup>129</sup>. This rhythm is thought to be driven by brainstem nuclei via projections through the medial septum<sup>130</sup>, and is universally reduced by anxiolytic drugs<sup>131</sup>. This HPC theta rhythm has been shown to entrain both single unit activity in pyramidal cells and interneurons of the PFC, as well as PFC gamma band activity<sup>132</sup>. Synchronization of PFC activity to the HPC theta rhythm has been observed within anxiety assays; in the threatening zones of the EPM and OFT (open arms and center, respectively), theta activity has been observed in the mPFC which is entrained to vHPC theta<sup>129</sup>. Theta rhythm synchrony between HPC and amygdala may underlie anxiety behaviors, as well, as crosscorrelation of activity in the theta frequency in LA and CA1 increase in response to the CS following fear conditioning<sup>133</sup>. Following extinction of fear conditioning, spontaneous freezing to the extinguished CS, representing an inappropriate assessment of threat, is associated with synchronized theta rhythms among IL, CA1 of HPC, and LA<sup>134</sup>. Moreover, there is a greater degree of theta coherence between these regions in serotonin receptor 1A knock out mice, which serve as a genetic mouse model of trait anxiety, relative to wild type controls<sup>129</sup>. Disruption of the vHPC theta rhythm using pharmacological blockade of gap junctions reduces anxiety-like behaviors in the EPM and OFT, and disconnection of LFP coherence by unilateral administration of gap junction blockers in contralateral vHPC and mPFC reduces theta activity in both regions as well as innate anxiety-like behaviors in ethological tasks<sup>135</sup>. vHPC-originating theta rhythms potentially enable the mPFC to construct representations of aversive features in

the environment, as mPFC neurons with strong task-related responses are strongly coupled to the vHPC theta rhythm<sup>136</sup>. Together, these data suggest that the vHPC theta rhythm conveys an anxiogenic signal to the mPFC and BLA.

Theta rhythms originating in the mPFC, however, provide a “safety” signal to BLA neurons. These theta rhythms originate in the mPFC as a result of phasic inhibition of parvalbumin interneurons residing there, which mediates local theta rhythm phase resetting<sup>107</sup>. Following successful extinction of fear learning, IL spike firing has been observed to lead the theta rhythm in HPC and LA during presentations of the CS<sup>134</sup>. Conversely, artificial theta synchronization of LA and HPC during extinction recall (such that PFC firing no longer leads these rhythms) increases freezing to the CS<sup>137</sup>. BLA field potentials and spike activity are entrained to the mPFC theta rhythm during periods of perceived safety (e.g., when mice enter the relative safety of the periphery of the open field<sup>32</sup>). This synchronization of BLA oscillations to mPFC during safety also extends to other LFP frequency bands in the BLA, including theta-coupled-gamma (40-120 Hz), particularly in the fast gamma (70-120 Hz) range<sup>138</sup>. Uncoupling of PFC theta oscillations from the HPC theta could in part be mediated by reciprocal inputs from the BLA to the PFC, which heterosynaptically suppress the influence of HPC inputs there<sup>139</sup>. Based upon the opposing contributions of PL and IL to fear learning and anxiety, the PFC safety signal likely originates in the IL. Thus, oscillatory activity among vHPC, mPFC, and BLA appears to reflect the internal anxiety state. The dominant source of theta activity may dynamically shift between the vHPC and mPFC in periods of relative threat and security in order to aid in the interpretation and evaluation of environmental events and support circuit level activity promoting defensive or exploratory behaviors.

### **Perspective on the Neural Circuitry of Anxiety**

We emphasize that limbic circuits are loops, rather than one-way streams of information flow. Anxiety arises from activity within these circuits when ambiguous environmental stimuli are *interpreted* as threatening. For this interpretation to occur, an organism must first detect that the stimuli exist through its sensory systems. Once potential threats are detected, the highly interconnected circuits described here interpret the meaning of those stimuli, and determine whether they portend danger. This interpretation is in part dictated by the individual’s previous experience, and includes the assignment of valence to the stimulus via BLA circuits<sup>56</sup>. Following the interpretation of an ambiguous event, additional circuits including the PFC and nuclei at the intersection of the limbic system and motor effectors<sup>140</sup> must evaluate whether the external events reflect expectations and if they meet or contradict the animal’s needs in order to



engage the appropriate behavioral response. Consequently, that response is initiated through downstream motor pathways, brainstem nuclei in control of autonomic responses, and the neuroendocrine system. Activation of these effectors results in the observable responses that we identify as anxiety or lack thereof.

Based upon this model (schematized in Figure 4), we conceive of anxiety as occurring between the stimulus and response, at the level of internal processing. Two individuals may equivalently detect a particular stimulus, but different interpretation of that stimulus may result in the selection of opposing behavioral responses. For example, a sudden, loud noise might be interpreted as fireworks by one person and as a gunshot by another, leading the first to curiously look to the sky and the second to duck and cover. The selected response also depends upon the *evaluation* of potential threat compared against *actual* threat (as determined by previous learning), as well as the individual's drive state. For instance, if an animal is thirsty, it will risk visiting the watering hole despite interpreting the setting as threatening. In fact, this approach-avoidance conflict resulting from the incongruity between the animal's needs and the interpretation of threat promotes vigilance and apprehension which serve a protective function for the animal and produce behaviors we can measure as anxiety (see "Measuring Anxiety-Like Behavior in Rodents," above). Although we cannot measure the internal state or emotional experience of an animal, we can determine which circuits govern the *interpretation* and *evaluation* of environmental stimuli and result in the selection of such anxiety-like behaviors.

Whether or not events are interpreted as threatening depends upon balance between circuits supporting exploratory versus defensive behaviors. An important mechanism that may allow one system to overcome the other is the recruitment of projection defined populations of neurons within the BLA. Positive and negative valence are oppositely encoded by BLA neurons projecting to canonical reward and fear systems (NAc and CeM, respectively,<sup>63</sup>), and specific activation of CeM-projecting BLA neurons might bias the *interpretation system* toward a "threat" appraisal. The relative strengths of these competing circuits may also contribute to interpretations of danger in the environment; for instance, repeated exposure to stressors or threatening stimuli may cause specific potentiation of circuits promoting anxiety-related behavior, such that in ambiguous situations, anxiety circuits prevail. Natural variations in the expression of certain genes may also impact the function of the *interpretation system*. For instance, the release of monoamines such as serotonin at different nuclei within the corticolimbic network impacts anxiety (i.e., innate anxiety-like behaviors in the EPM are associated with decreased levels of serotonin in the mPFC, amygdala, and HPC<sup>141</sup>), and polymorphisms in the serotonin transporter gene have been found to influence trait anxiety in

rodents and humans<sup>142,143</sup>. These findings are particularly interesting in light of the efficacy of SSRIs and SNRIs in the treatment of anxiety.

Here, we reframe corticolimbic circuitry from the perspective of anxiety. The model that we propose builds upon existing models, within the framework of *detection*, *interpretation*, *evaluation*, and *response initiation*. For example, both bottom-up and top-down processes determine which external events will be detected<sup>144</sup>; top-down suppression of attention to ambiguous stimuli may reduce the anxiety response. Furthermore, the valence detection function of BLA projection neurons<sup>56</sup> fits within the interpretation circuits described here, helping to determine whether a given stimulus is threatening or appetitive. Actor-critic models<sup>145-147</sup> operate within the *evaluation system*; dopamine inputs to the striatum push the animal toward obtaining maximum reward, a process which must take into account possible dangers. These dangers are recognized by interpretation circuits, and fed into the actor-critic interplay occurring within evaluation circuits, subsequently determining what course of action must be taken. This action is taken as a result of increased activity within the basal ganglia, which serve as the limbic-motor interface<sup>140</sup>, and facilitate the initiation of motor responses following upstream processing in the *interpretation system*.

To select appropriate behavioral responses within a given environmental context, an animal must weigh potential rewards against potential risks. To use a balance metaphor, interpretation circuits may determine the relative weight of various environmental stimuli on either end of the balance while evaluation circuits govern the location of the fulcrum that influences the balance point.

### **Circuit-based Intervention: The Future of Anxiety Therapy**

In cases of pathological anxiety, excessive apprehension occurs in response to minimally threatening stimuli or even in the absence of provocation, implying dysfunction at the level of interpretation. Bias of the system toward rendering a “threat” interpretation in the absence of probable danger may result from undue Hebbian plasticity in limbic pathways (particularly in “cued” anxiety disorders, such as social anxiety disorder and specific phobias), or may be the outcome of a disruption to homeostatic mechanisms that normally maintain balance between circuits supporting defensive versus exploratory behaviors (particularly in persistent anxiety, such as generalized anxiety disorder).

Because disruption to any one part of a highly interconnected system results in changes to the whole, effective solutions necessitate interventions which consider the dynamics of the entire system. Likewise, future therapies for anxiety disorders must take a circuit-level

approach. We have previously extolled neural circuit reprogramming, in which the brain's own plasticity mechanisms are directed toward resolving the symptoms of psychiatric illnesses, as a promising future therapeutic strategy to work toward<sup>20</sup>. Targeted plasticity, perhaps via transcranial magnetic stimulation (TMS) or focal ultrasound, directed at certain nodes within the circular loops described in this review could elicit positive downstream changes ameliorating undesirable anxiety. For example, potentiation of inputs from IL to the BLA could enhance so called "safety" signals, and depotentiation of BLA inputs to the CeM could reduce the expression of learned fear associations. There is reason to believe that neural circuit reprogramming is a viable future strategy for the treatment of anxiety disorders; already it has been shown that fear memories can be turned "on" and "off" via induction of LTP and LTD in amygdalar microcircuits<sup>148</sup>. Moreover, the best intervention currently available for the treatment of anxiety disorders is cognitive-behavioral therapy (CBT)<sup>149</sup>, which aims to replace maladaptive interpretations of events with more helpful ones, a process which almost certainly occurs through plastic changes within the interpretation circuits described here.

Before this innovative strategy can become reality, however, a comprehensive understanding of the dynamic interactions occurring within the distributed networks underlying anxiety is needed. Although this prospect seems somewhat daunting, inroads are rapidly being made that advance the current state of knowledge toward this goal. Optogenetic studies of individual pathways within circuits subserving interpretation and evaluation of external stimuli provide valuable insights into how individual components of the system function. Work toward mapping the neural connectome could potentially identify novel pathways among genetically defined populations of cells that will supply avenues for future discovery<sup>150</sup>.

One important clue as to how these highly interconnected pathways might interact and impact each other's activity may be derived from investigating the comorbidity among psychiatric disorders. Although comorbidities are systematically eliminated in pharmaceutical drug development, the overlapping constellations of symptoms might shed light upon which aspects of the neural substrates of these symptoms co-vary. For instance, substance abuse and addiction are often coincident with anxiety disorders, however the symptoms of anxiety or depression in an addicted person may not be observable until the addictive substance is withdrawn. Studying a comorbid individual in both states might unveil how the interconnected loops shift dominance during different emotional and behavioral states, and provide novel targets for future treatment strategies.

Treating complex psychiatric disorders that arise from disruption to complex, highly interconnected neural systems requires a broad, circuit-level approach. A paradigm shift in how

we consider the neural substrates underpinning anxiety – such that individual nodes of larger circuits are not interrogated in a vacuum, independent of the larger circuits – promises to transform how these most common of mental illnesses are treated.

**Call-out Boxes:***Prevalence*

Prevalence – the proportion of a population with a condition

Lifetime prevalence – the proportion of a population that will experience the condition at some point during their lives

*Validity*

Face validity – the extent to which observable phenotypes in the animal reproduce the human condition; the anxiety response of the animal should be behaviorally and physiologically similar to the anxiety response in humans.

Predictive validity – the extent to which pharmacological agents that reduce anxiety in model organisms also reduce anxiety in humans; anxiety in animals should be sensitive to clinically effective anxiolytics.

Construct validity – the extent to which the underlying causes of the human condition and phenotypes in the animal are equivalent; an animal model of anxiety should result from the same neurobiological processes as anxiety in humans.

## Figure Legends

**Figure 1. Few novel pharmacotherapies for the treatment of anxiety have been developed since the 1940s.** The cumulative FDA approvals of medications with an indication for anxiety (blue line) are compared to those for medications with an indication for hypertension (gray line), a more thoroughly understood condition. In addition to the comparatively slow rate of overall approvals of anxiolytics, a lesser number of mechanistically novel targets have been identified for the treatment of anxiety than hypertension during the past 75 years (inset). The relative paucity of pharmacological strategies for the treatment of anxiety disorders and the imperfect efficacy of these drugs belies a need for a more thorough understanding of the neural substrates of anxiety.

**Figure 2. Validated tests to assay anxiety and related emotional states in mice.** State anxiety in mice is measured behaviorally through a variety of tests, highlighted in orange. Exemplars of fear and physiological stress assays are also illustrated in red and yellow, respectively.

**Figure 3. Neural circuits implicated in anxiety-related behaviors in the rodent brain.**

Recent work using optogenetics, behavioral neuroscience, and electrophysiology has begun to establish causal relationships between anxiety behaviors and activity in specific neural circuits. **a**, Cartoon of sagittal view of rodent brain including distal circuits implicated in anxiety-related behaviors. **b**, Septohippocampal microcircuitry linked to anxiety. **c** and **d**, Extended amygdala microcircuits involved in anxiety-related behaviors, including BLA projections to the BNST (**c**) and BLA projections to CeA (**d**). Abbreviations: ad, anterodorsal nucleus of the BNST; AHA, anterior hypothalamic area; BLA, basolateral amygdala; BNST, bed nucleus of the stria terminalis; CeA, central amygdala; CeL, lateral subdivision of the central amygdala; CeM, centromedial subdivision of the amygdala; CrFr2 $\alpha$ , type 2 CRF receptor; DR, dorsal raphe nucleus; DVC, dorsal vagal complex; HPC, hippocampus; Hyp, hypothalamus; IL, infralimbic division of the mPFC; LC, locus coeruleus; LH, lateral hypothalamus; LS, lateral septum; mPFC, medial prefrontal cortex; NAc, nucleus accumbens; ov, oval BNST; PAG, periaqueductal gray; PB, parabrachial nucleus; PKC $\delta$ +, protein kinase c delta positive; PKC $\delta$ -, protein kinase c delta negative; PL, prelimbic division of the mPFC; PVH, paraventricular nucleus of the hypothalamus; PVT, paraventricular thalamus; SI, substantia innominata; Thal, thalamus; vHPC, ventral hippocampus; VTA, ventral tegmental area.

**Figure 4. Circuit organization in anxiety: A problem with Interpretation.** We propose a model wherein external events are *detected, interpreted, evaluated, and responded to* by succeeding levels of highly interconnected neural circuits. Whether events are interpreted as threatening or non-threatening depends upon balance between opposing circuits among the amygdala, vHPC, mPFC, and BNST. In anxiety, balance is shifted toward projections interpreting events as threatening. Red, anxiogenic pathway; blue, anxiolytic pathway.

Abbreviations: ad, anterodorsal nucleus of the BNST; AHA, anterior hypothalamic area; BLA, basolateral amygdala; BNST, bed nucleus of the stria terminalis; CeA, central amygdala; CeL, lateral subdivision of the central amygdala; CeM, centromedial subdivision of the amygdala; DVC, dorsal vagal complex; IL, infralimbic division of the mPFC; LH, lateral hypothalamus; LS, lateral septum; mPFC, medial prefrontal cortex; NAc, nucleus accumbens; ov, oval BNST; PAG, periaqueductal gray; PB, parabrachial nucleus; PL, prelimbic division of the mPFC; PVH, paraventricular nucleus of the hypothalamus; v, ventral BNST; vHPC, ventral hippocampus; vPallidum, ventral pallidum; VTA, ventral tegmental area

## **Acknowledgments**

We thank Michael Kinch and Mazen Kheirbek for helpful correspondence, Caitlin Vander Weele and Romy Wichmann for careful reading and comments on our text, and the entire Tye Laboratory for stimulating discussion. K.M.T. is a New York Stem Cell Foundation - Robertson Investigator, and this work was supported by funding from the JPB Foundation, PIIF, PNDRF, JFDP, Whitehall Foundation, Klingenstein Foundation, McKnight Foundation, NARSAD Young Investigator Award, Alfred P Sloan Foundation, New York Stem Cell Foundation, Whitehead Career Development Chair, NIH R01-MH102441-01 (NIMH) and NIH Director's New Innovator Award DP2-DK-102256-01 (NIDDK). G.G.C. is supported by the JFDP Postdoctoral Fellowship from the JPB Foundation.

We declare that the authors have no competing interests as defined by Nature Publishing Group, or other interests that might be perceived to influence the results and/or discussion reported in this article.



## References

1. Hull, C. L. *Principles of Behavior: An Introduction to Behavior Theory*. (Appleton-Century-Crofts, Inc., 1943).
2. Darwin, C. *The Expression of the Emotions in Man and Animals*. (Impression anastaltique Culture et Civilisation, 1872).
3. LeDoux, J. Rethinking the Emotional Brain. *Neuron* **73**, 653–676 (2012).
4. Panksepp, J. Affective consciousness: Core emotional feelings in animals and humans. *Conscious. Cogn.* **14**, 30–80 (2005).
5. Anderson, D. J. & Adolphs, R. A framework for studying emotions across species. *Cell* **157**, 187–200 (2014).
6. Russell, J. A. A circumplex model of affect. *J. Pers. Soc. Psychol.* **39**, 1161–1178 (1980).
7. Davis, M., Walker, D. L., Miles, L. & Grillon, C. Phasic vs sustained fear in rats and humans: role of the extended amygdala in fear vs anxiety. *Neuropsychopharmacol. Off. Publ. Am. Coll. Neuropsychopharmacol.* **35**, 105–135 (2010).
8. American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders*. (American Psychiatric Association, 2013). at <http://dsm.psychiatryonline.org/doi/book/10.1176/appi.books.9780890425596>
9. Bereza, B. G., Machado, M. & Einarson, T. R. Systematic review and quality assessment of economic evaluations and quality-of-life studies related to generalized anxiety disorder. *Clin. Ther.* **31**, 1279–1308 (2009).
10. Mondin, T. C. *et al.* Anxiety disorders in young people: a population-based study. *Rev. Bras. Psiquiatr. São Paulo Braz.* 1999 **35**, 347–352 (2013).

11. Pagotto, L. F. *et al.* The impact of posttraumatic symptoms and comorbid mental disorders on the health-related quality of life in treatment-seeking PTSD patients. *Compr. Psychiatry* **58**, 68–73 (2015).
12. Kessler, R. C., Chiu, W. T., Demler, O., Merikangas, K. R. & Walters, E. E. Prevalence, severity, and comorbidity of 12-month DSM-IV disorders in the National Comorbidity Survey Replication. *Arch. Gen. Psychiatry* **62**, 617–627 (2005).
13. Kessler, R. C. *et al.* Lifetime prevalence and age-of-onset distributions of DSM-IV disorders in the National Comorbidity Survey Replication. *Arch. Gen. Psychiatry* **62**, 593–602 (2005).
14. Lecrubier, Y. Widespread underrecognition and undertreatment of anxiety and mood disorders: results from 3 European studies. *J. Clin. Psychiatry* **68 Suppl 2**, 36–41 (2007).
15. Berlin, H. A., Hamilton, H. & Hollander, E. Experimental therapeutics for refractory obsessive-compulsive disorder: translational approaches and new somatic developments. *Mt. Sinai J. Med. N. Y.* **75**, 174–203 (2008).
16. Davidson, J. R. *et al.* A psychopharmacological treatment algorithm for generalised anxiety disorder (GAD). *J. Psychopharmacol. Oxf. Engl.* **24**, 3–26 (2010).
17. Hoffman, E. J. & Mathew, S. J. Anxiety disorders: a comprehensive review of pharmacotherapies. *Mt. Sinai J. Med. J. Transl. Pers. Med.* **75**, 248–262 (2008).
18. Kinch, M. S., Haynesworth, A., Kinch, S. L. & Hoyer, D. An overview of FDA-approved new molecular entities: 1827-2013. *Drug Discov. Today* **19**, 1033–1039 (2014).
19. U.S. Food and Drug Administration. Drugs@FDA. at <http://www.accessdata.fda.gov/scripts/cder/drugsatfda/index.cfm>
20. Tye, K. M. Neural circuit reprogramming: a new paradigm for treating neuropsychiatric disease? *Neuron* **83**, 1259–1261 (2014).

21. Allsop, S. A., Vander Weele, C. M., Wichmann, R. & Tye, K. M. Optogenetic insights on the relationship between anxiety-related behaviors and social deficits. *Front. Behav. Neurosci.* **8**, 241 (2014).
22. Belzung, C. & Griebel, G. Measuring normal and pathological anxiety-like behaviour in mice: a review. *Behav. Brain Res.* **125**, 141–149 (2001).
23. Cryan, J. F. & Holmes, A. The ascent of mouse: advances in modelling human depression and anxiety. *Nat. Rev. Drug Discov.* **4**, 775–790 (2005).
24. Sylvers, P., Lilienfeld, S. O. & LaPrairie, J. L. Differences between trait fear and trait anxiety: implications for psychopathology. *Clin. Psychol. Rev.* **31**, 122–137 (2011).
25. Lister, R. G. Ethologically-based animal models of anxiety disorders. *Pharmacol. Ther.* **46**, 321–340 (1990).
26. Adhikari, A. Distributed circuits underlying anxiety. *Front. Behav. Neurosci.* **8**, 112 (2014).
27. Degroot, A. & Treit, D. Anxiety is functionally segregated within the septo-hippocampal system. *Brain Res.* **1001**, 60–71 (2004).
28. Eden, A. S. *et al.* Emotion Regulation and Trait Anxiety Are Predicted by the Microstructure of Fibers between Amygdala and Prefrontal Cortex. *J. Neurosci. Off. J. Soc. Neurosci.* **35**, 6020–6027 (2015).
29. Etkin, A., Prater, K. E., Schatzberg, A. F., Menon, V. & Greicius, M. D. Disrupted amygdalar subregion functional connectivity and evidence of a compensatory network in generalized anxiety disorder. *Arch. Gen. Psychiatry* **66**, 1361–1372 (2009).
30. Irle, E. *et al.* Reduced amygdalar and hippocampal size in adults with generalized social phobia. *J. Psychiatry Neurosci. JPN* **35**, 126–131 (2010).
31. Kim, S.-Y. *et al.* Diverging neural pathways assemble a behavioural state from separable features in anxiety. *Nature* **496**, 219–223 (2013).

**First study to provide causal evidence that separate circuits control the behavioral and physiological features of anxiety.**

32. Likhtik, E., Stujenske, J. M., Topiwala, M. A., Harris, A. Z. & Gordon, J. A. Prefrontal entrainment of amygdala activity signals safety in learned fear and innate anxiety. *Nat. Neurosci.* **17**, 106–113 (2014).

**Identifies a macrocircuit-level mechanism to discern “safety” from threat, whereby BLA firing is tuned to mPFC oscillatory activity.**

33. Tye, K. M. *et al.* Amygdala circuitry mediating reversible and bidirectional control of anxiety. *Nature* **471**, 358–362 (2011).

**Original optogenetic dissection of the control of anxiety by separate aspects of the BLA microcircuit and first study to employ projection-specific optogenetic manipulations of behavior.**

34. Yassa, M. A., Hazlett, R. L., Stark, C. E. L. & Hoehn-Saric, R. Functional MRI of the amygdala and bed nucleus of the stria terminalis during conditions of uncertainty in generalized anxiety disorder. *J. Psychiatr. Res.* **46**, 1045–1052 (2012).
35. Pellow, S., Chopin, P., File, S. E. & Briley, M. Validation of open:closed arm entries in an elevated plus-maze as a measure of anxiety in the rat. *J. Neurosci. Methods* **14**, 149–167 (1985).
36. Shepherd, J. K., Grewal, S. S., Fletcher, A., Bill, D. J. & Dourish, C. T. Behavioural and pharmacological characterisation of the elevated ‘zero-maze’ as an animal model of anxiety. *Psychopharmacology (Berl.)* **116**, 56–64 (1994).
37. Hall, C. & Ballachey, E. L. A study of the rat’s behavior in a field. A contribution to method in comparative psychology. *Univ. Calif. Publ. Psychol.* **6**, 1–12 (1932).
38. Ambrogio Lorenzini, C., Bucherelli, C. & Giachetti, A. Passive and active avoidance behavior in the light-dark box test. *Physiol. Behav.* **32**, 687–689 (1984).
39. Simiand, J., Keane, P. E. & Morre, M. The staircase test in mice: a simple and efficient procedure for primary screening of anxiolytic agents. *Psychopharmacology (Berl.)* **84**, 48–53 (1984).

40. Kalueff, A. V. *et al.* The regular and light-dark Suok tests of anxiety and sensorimotor integration: utility for behavioral characterization in laboratory rodents. *Nat. Protoc.* **3**, 129–136 (2008).
41. File, S. E. & Wardill, A. G. The reliability of the hole-board apparatus. *Psychopharmacologia* **44**, 47–51 (1975).
42. Borsini, F., Podhorna, J. & Marazziti, D. Do animal models of anxiety predict anxiolytic-like effects of antidepressants? *Psychopharmacology (Berl.)* **163**, 121–141 (2002).
43. Degroot, A. & Nomikos, G. G. Genetic deletion and pharmacological blockade of CB1 receptors modulates anxiety in the shock-probe burying test. *Eur. J. Neurosci.* **20**, 1059–1064 (2004).
44. Njung'e, K. & Handley, S. L. Evaluation of marble-burying behavior as a model of anxiety. *Pharmacol. Biochem. Behav.* **38**, 63–67 (1991).
45. Nicolas, L. B., Kolb, Y. & Prinssen, E. P. M. A combined marble burying-locomotor activity test in mice: a practical screening test with sensitivity to different classes of anxiolytics and antidepressants. *Eur. J. Pharmacol.* **547**, 106–115 (2006).
46. Treit, D., Pinel, J. P. J. & Fibiger, H. C. Conditioned defensive burying: A new paradigm for the study of anxiolytic agents. *Pharmacol. Biochem. Behav.* **15**, 619–626 (1981).
47. Dulawa, S. C., Holick, K. A., Gundersen, B. & Hen, R. Effects of chronic fluoxetine in animal models of anxiety and depression. *Neuropsychopharmacol. Off. Publ. Am. Coll. Neuropsychopharmacol.* **29**, 1321–1330 (2004).
48. Merali, Z., Levac, C. & Anisman, H. Validation of a simple, ethologically relevant paradigm for assessing anxiety in mice. *Biol. Psychiatry* **54**, 552–565 (2003).
49. Sánchez, C. Stress-induced vocalisation in adult animals. A valid model of anxiety? *Eur. J. Pharmacol.* **463**, 133–143 (2003).
50. Gardner, C. R. Distress vocalization in rat pups. A simple screening method for anxiolytic drugs. *J. Pharmacol. Methods* **14**, 181–187 (1985).

51. File, S. E. Animal models for predicting clinical efficacy of anxiolytic drugs: social behaviour. *Neuropsychobiology* **13**, 55–62 (1985).
52. Viviani, D. *et al.* Oxytocin selectively gates fear responses through distinct outputs from the central amygdala. *Science* **333**, 104–107 (2011).

**Identification of discrete CeA efferent pathways separately regulating behavioral and physiological fear responses.**

53. Duvarci, S. & Pare, D. Amygdala microcircuits controlling learned fear. *Neuron* **82**, 966–980 (2014).
54. Brown, S. & Schäfer, E. An investigation into the functions of the occipital and temporal lobes of the monkey's brain. *Philos. Trans. R. Soc. Lond. B* **179**, 303–327 (1888).
55. McDonald, A. J. Cortical pathways to the mammalian amygdala. *Prog. Neurobiol.* **55**, 257–332 (1998).
56. Janak, P. H. & Tye, K. M. From circuits to behaviour in the amygdala. *Nature* **517**, 284–292 (2015).
57. Maren, S. & Quirk, G. J. Neuronal signalling of fear memory. *Nat. Rev. Neurosci.* **5**, 844–852 (2004).
58. McKernan, M. G. & Shinnick-Gallagher, P. Fear conditioning induces a lasting potentiation of synaptic currents in vitro. *Nature* **390**, 607–611 (1997).
59. Rogan, M. T., Stäubli, U. V. & LeDoux, J. E. Fear conditioning induces associative long-term potentiation in the amygdala. *Nature* **390**, 604–607 (1997).
60. LeDoux, J. E. Emotion circuits in the brain. *Annu. Rev. Neurosci.* **23**, 155–184 (2000).
61. Tye, K. M. & Janak, P. H. Amygdala neurons differentially encode motivation and reinforcement. *J. Neurosci. Off. J. Soc. Neurosci.* **27**, 3937–3945 (2007).
62. Tye, K. M., Stuber, G. D., de Ridder, B., Bonci, A. & Janak, P. H. Rapid strengthening of thalamo-amygdala synapses mediates cue-reward learning. *Nature* **453**, 1253–1257 (2008).
63. Namburi, P. *et al.* A circuit mechanism for differentiating positive and negative associations. *Nature* **520**, 675–678 (2015).

**First evidence of largely non-overlapping, projection target-defined populations of neurons within the BLA oppositely encoding valence in fear and reward learning.**

64. Tye, K. M. & Deisseroth, K. Optogenetic investigation of neural circuits underlying brain disease in animal models. *Nat. Rev. Neurosci.* **13**, 251–266 (2012).
65. Fox, A. S., Oler, J. A., Tromp, D. P. M., Fudge, J. L. & Kalin, N. H. Extending the amygdala in theories of threat processing. *Trends Neurosci.* **38**, 319–329 (2015).
66. Felix-Ortiz, A. C. *et al.* BLA to vHPC inputs modulate anxiety-related behaviors. *Neuron* **79**, 658–664 (2013).

**Provides the first direct evidence of bidirectional control of anxiety via the BLA projection to vHPC.**

67. Herry, C. *et al.* Switching on and off fear by distinct neuronal circuits. *Nature* **454**, 600–606 (2008).
68. Hübner, C., Bosch, D., Gall, A., Lüthi, A. & Ehrlich, I. Ex vivo dissection of optogenetically activated mPFC and hippocampal inputs to neurons in the basolateral amygdala: implications for fear and emotional memory. *Front. Behav. Neurosci.* **8**, 64 (2014).
69. Herry, C. & Johansen, J. P. Encoding of fear learning and memory in distributed neuronal circuits. *Nat. Neurosci.* **17**, 1644–1654 (2014).
70. Johansen, J. P. *et al.* Optical activation of lateral amygdala pyramidal cells instructs associative fear learning. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 12692–12697 (2010).
71. Quirk, G. J., Repa, C. & LeDoux, J. E. Fear conditioning enhances short-latency auditory responses of lateral amygdala neurons: parallel recordings in the freely behaving rat. *Neuron* **15**, 1029–1039 (1995).
72. Ciocchi, S. *et al.* Encoding of conditioned fear in central amygdala inhibitory circuits. *Nature* **468**, 277–282 (2010).

**Optogenetic interrogation of amygdala microcircuits controlling learned fear based upon neural response profiles. (see also, companion paper: Haubensak *et al.*, 2010)**

73. Haubensak, W. *et al.* Genetic dissection of an amygdala microcircuit that gates conditioned fear.

*Nature* **468**, 270–276 (2010).

**Optogenetic dissection of the control of learned fear by genetically defined populations of neurons within the amygdala microcircuit. (see also, companion paper: Ciocchi et al., 2010)**

74. Cai, H., Haubensak, W., Anthony, T. E. & Anderson, D. J. Central amygdala PKC- $\delta$ + neurons mediate the influence of multiple anorexigenic signals. *Nat. Neurosci.* **advance online publication**, (2014).

**Presents the first causal evidence that a population of CeL neurons mediate inhibition of feeding, and also demonstrates that activity in these cells is not anxiogenic.**

75. Li, H. *et al.* Experience-dependent modification of a central amygdala fear circuit. *Nat. Neurosci.*

**16**, 332–339 (2013).

**Presents the first evidence of fear conditioning-induced plasticity in the CeL.**

76. Penzo, M. A., Robert, V. & Li, B. Fear conditioning potentiates synaptic transmission onto long-range projection neurons in the lateral subdivision of central amygdala. *J. Neurosci. Off. J. Soc. Neurosci.* **34**, 2432–2437 (2014).

*Neurosci.* **34**, 2432–2437 (2014).

77. Penzo, M. A. *et al.* The paraventricular thalamus controls a central amygdala fear circuit. *Nature*

**519**, 455–459 (2015).

78. Tovote, P., Fadok, J. P. & Lüthi, A. Neuronal circuits for fear and anxiety. *Nat. Rev. Neurosci.* **16**,

317–331 (2015).

79. Wang, D. V. *et al.* Neurons in the amygdala with response-selectivity for anxiety in two

ethologically based tests. *PLoS One* **6**, e18739 (2011).



80. Huff, M. L., Miller, R. L., Deisseroth, K., Moorman, D. E. & LaLumiere, R. T. Posttraining optogenetic manipulations of basolateral amygdala activity modulate consolidation of inhibitory avoidance memory in rats. *Proc. Natl. Acad. Sci. U. S. A.* **110**, 3597–3602 (2013).
81. Cullinan, W. E., Herman, J. P. & Watson, S. J. Ventral subicular interaction with the hypothalamic paraventricular nucleus: evidence for a relay in the bed nucleus of the stria terminalis. *J. Comp. Neurol.* **332**, 1–20 (1993).
82. Dong, H. W., Petrovich, G. D. & Swanson, L. W. Topography of projections from amygdala to bed nuclei of the stria terminalis. *Brain Res. Brain Res. Rev.* **38**, 192–246 (2001).
83. Stamatakis, A. M. *et al.* Amygdala and bed nucleus of the stria terminalis circuitry: Implications for addiction-related behaviors. *Neuropharmacology* **76 Pt B**, 320–328 (2014).
84. Poulos, A. M., Ponnusamy, R., Dong, H.-W. & Fanselow, M. S. Compensation in the neural circuitry of fear conditioning awakens learning circuits in the bed nuclei of the stria terminalis. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 14881–14886 (2010).
85. Jennings, J. H. *et al.* Distinct extended amygdala circuits for divergent motivational states. *Nature* **496**, 224–228 (2013).

**Presents causal evidence of functionally opposed, neurochemically defined populations of projection neurons within a single efferent pathway.**

86. Christianson, J. P. *et al.* Safety signals mitigate the consequences of uncontrollable stress via a circuit involving the sensory insular cortex and bed nucleus of the stria terminalis. *Biol. Psychiatry* **70**, 458–464 (2011).
87. Van Strien, N. M., Cappaert, N. L. M. & Witter, M. P. The anatomy of memory: an interactive overview of the parahippocampal-hippocampal network. *Nat. Rev. Neurosci.* **10**, 272–282 (2009).
88. Witter, M. P., Canto, C. B., Couey, J. J., Koganezawa, N. & O'Reilly, K. C. Architecture of spatial circuits in the hippocampal region. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **369**, 20120515 (2014).

89. Amaral, D. & Lavenex, P. in *The Hippocampus Book* (eds. Anderson, P., Morris, R., Amaral, D., Bliss, T. & O'Keefe, J.) 37–114 (Oxford University Press, 2007).
90. Sparta, D. R. *et al.* Inhibition of projections from the basolateral amygdala to the entorhinal cortex disrupts the acquisition of contextual fear. *Front. Behav. Neurosci.* **8**, 129 (2014).
91. Kheirbek, M. A. *et al.* Differential control of learning and anxiety along the dorsoventral axis of the dentate gyrus. *Neuron* **77**, 955–968 (2013).

**Using optogenetics, clarifies the specific influence of dorsal and ventral dentate gyrus to exploration and encoding of fear association versus innate anxiety, respectively.**

92. Mori, M., Abegg, M. H., Gähwiler, B. H. & Gerber, U. A frequency-dependent switch from inhibition to excitation in a hippocampal unitary circuit. *Nature* **431**, 453–456 (2004).
93. Risold, P. Y. & Swanson, L. W. Structural evidence for functional domains in the rat hippocampus. *Science* **272**, 1484–1486 (1996).
94. Risold, P. Y. & Swanson, L. W. Connections of the rat lateral septal complex. *Brain Res. Brain Res. Rev.* **24**, 115–195 (1997).
95. Trent, N. L. & Menard, J. L. The ventral hippocampus and the lateral septum work in tandem to regulate rats' open-arm exploration in the elevated plus-maze. *Physiol. Behav.* **101**, 141–152 (2010).
96. Henry, B., Vale, W. & Markou, A. The effect of lateral septum corticotropin-releasing factor receptor 2 activation on anxiety is modulated by stress. *J. Neurosci. Off. J. Soc. Neurosci.* **26**, 9142–9152 (2006).
97. Anthony, T. E. *et al.* Control of stress-induced persistent anxiety by an extra-amygdala septohypothalamic circuit. *Cell* **156**, 522–536 (2014).

**First optogenetic interrogation of the septohippocampal system in anxiety, which has not been otherwise evaluated using modern tools.**

98. Gross, J. J. The emerging field of emotion regulation: An integrative review. *Rev. Gen. Psychol.* **2**, 271–299 (1998).
99. Markram, H. *et al.* Interneurons of the neocortical inhibitory system. *Nat. Rev. Neurosci.* **5**, 793–807 (2004).
100. Van De Werd, H. J. J. M. & Uylings, H. B. M. Comparison of (stereotactic) parcellations in mouse prefrontal cortex. *Brain Struct. Funct.* **219**, 433–459 (2014).
101. Groenewegen, H. J., Wright, C. I. & Uylings, H. B. The anatomical relationships of the prefrontal cortex with limbic structures and the basal ganglia. *J. Psychopharmacol. Oxf. Engl.* **11**, 99–106 (1997).
102. Kim, M. J. *et al.* The structural and functional connectivity of the amygdala: From normal emotion to pathological anxiety. *Behav. Brain Res.* **223**, 403–410 (2011).
103. Ochsner, K. N., Bunge, S. A., Gross, J. J. & Gabrieli, J. D. E. Rethinking Feelings: An fMRI Study of the Cognitive Regulation of Emotion. *J. Cogn. Neurosci.* **14**, 1215–1229 (2002).
104. Livneh, U. & Paz, R. Amygdala-prefrontal synchronization underlies resistance to extinction of aversive memories. *Neuron* **75**, 133–142 (2012).
105. Senn, V. *et al.* Long-range connectivity defines behavioral specificity of amygdala neurons. *Neuron* **81**, 428–437 (2014).
106. Burgos-Robles, A., Vidal-Gonzalez, I. & Quirk, G. J. Sustained Conditioned Responses in Prelimbic Prefrontal Neurons Are Correlated with Fear Expression and Extinction Failure. *J. Neurosci.* **29**, 8474–8482 (2009).
107. Courtin, J. *et al.* Prefrontal parvalbumin interneurons shape neuronal activity to drive fear expression. *Nature* **505**, 92–96 (2014).

**Original causal demonstration that mPFC microcircuit dynamics locally produce the mPFC theta rhythm in order to control the timing of fear behaviors.**

108. Milad, M. R. & Quirk, G. J. Neurons in medial prefrontal cortex signal memory for fear extinction. *Nature* **420**, 70–74 (2002).
109. Baeg, E. H. *et al.* Fast spiking and regular spiking neural correlates of fear conditioning in the medial prefrontal cortex of the rat. *Cereb. Cortex N. Y. N* **1991** **11**, 441–451 (2001).
110. Chang, C., Berke, J. D. & Maren, S. Single-unit activity in the medial prefrontal cortex during immediate and delayed extinction of fear in rats. *PLoS One* **5**, e11971 (2010).
111. Holmes, A. *et al.* Chronic alcohol remodels prefrontal neurons and disrupts NMDAR-mediated fear extinction encoding. *Nat. Neurosci.* **15**, 1359–1361 (2012).
112. Maroun, M., Kavushansky, A., Holmes, A., Wellman, C. & Motanis, H. Enhanced extinction of aversive memories by high-frequency stimulation of the rat infralimbic cortex. *PLoS One* **7**, e35853 (2012).
113. Arruda-Carvalho, M. & Clem, R. L. Pathway-selective adjustment of prefrontal-amygdala transmission during fear encoding. *J. Neurosci. Off. J. Soc. Neurosci.* **34**, 15601–15609 (2014).
114. Do-Monte, F. H., Quiñones-Laracuente, K. & Quirk, G. J. A temporal shift in the circuits mediating retrieval of fear memory. *Nature* **519**, 460–463 (2015).
115. Likhtik, E. & Paz, R. Amygdala-prefrontal interactions in (mal)adaptive learning. *Trends Neurosci.* **38**, 158–166 (2015).
116. Grace, A. A. & Rosenkranz, J. A. Regulation of conditioned responses of basolateral amygdala neurons. *Physiol. Behav.* **77**, 489–493 (2002).
117. Likhtik, E., Pelletier, J. G., Paz, R. & Paré, D. Prefrontal control of the amygdala. *J. Neurosci. Off. J. Soc. Neurosci.* **25**, 7429–7437 (2005).
118. Rosenkranz, J. A., Moore, H. & Grace, A. A. The prefrontal cortex regulates lateral amygdala neuronal plasticity and responses to previously conditioned stimuli. *J. Neurosci. Off. J. Soc. Neurosci.* **23**, 11054–11064 (2003).

**Early demonstration, using technically challenging *in vivo* intracellular recordings, that mPFC can regulate affective processing via inhibition of amygdala activity.**

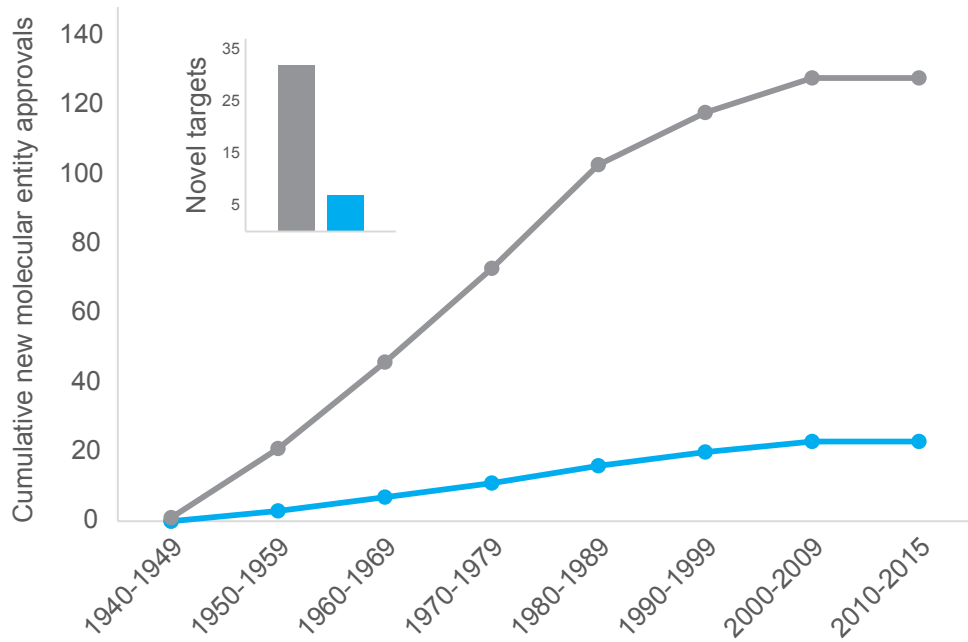
119. Calhoon, G. G. & O'Donnell, P. Closing the gate in the limbic striatum: prefrontal suppression of hippocampal and thalamic inputs. *Neuron* **78**, 181–190 (2013).
120. Britt, J. P. *et al.* Synaptic and behavioral profile of multiple glutamatergic inputs to the nucleus accumbens. *Neuron* **76**, 790–803 (2012).
121. Mackintosh, N. J. Neurobiology, psychology and habituation. *Behav. Res. Ther.* **25**, 81–97 (1987).
122. Byrne, J. H., Castellucci, V. F., Carew, T. J. & Kandel, E. R. Stimulus-response relations and stability of mechanoreceptor and motor neurons mediating defensive gill-withdrawal reflex in *Aplysia*. *J. Neurophysiol.* **41**, 402–417 (1978).
123. Balleine, B. W. Neural bases of food-seeking: Affect, arousal and reward in corticostriatolimbic circuits. *Physiol. Behav.* **86**, 717–730 (2005).
124. Orsini, C. A., Moorman, D. E., Young, J. W., Setlow, B. & Floresco, S. B. Neural mechanisms regulating different forms of risk-related decision-making: Insights from animal models. *Neurosci. Biobehav. Rev.* (2015). doi:10.1016/j.neubiorev.2015.04.009
125. Phillips, P. E. M., Walton, M. E. & Jhou, T. C. Calculating utility: preclinical evidence for cost-benefit analysis by mesolimbic dopamine. *Psychopharmacology (Berl.)* **191**, 483–495 (2007).
126. Opland, D. M., Leininger, G. M. & Myers, M. G. Modulation of the mesolimbic dopamine system by leptin. *Brain Res.* **1350**, 65–70 (2010).
127. Sternson, S. M. Hypothalamic survival circuits: blueprints for purposive behaviors. *Neuron* **77**, 810–824 (2013).
128. Nieh, E. H. *et al.* Decoding Neural Circuits that Control Compulsive Sucrose Seeking. *Cell* **160**, 528–541 (2015).



129. Adhikari, A., Topiwala, M. A. & Gordon, J. A. Synchronized activity between the ventral hippocampus and the medial prefrontal cortex during anxiety. *Neuron* **65**, 257–269 (2010).
- Early demonstration that vHPC (but not dHPC) theta rhythm synchrony with mPFC increases during anxiety.**
130. Vertes, R. P. & Kocsis, B. Brainstem-diencephalo-septohippocampal systems controlling the theta rhythm of the hippocampus. *Neuroscience* **81**, 893–926 (1997).
131. McNaughton, N., Kocsis, B. & Hajós, M. Elicited hippocampal theta rhythm: a screen for anxiolytic and procognitive drugs through changes in hippocampal function? *Behav. Pharmacol.* **18**, 329–346 (2007).
132. Sirota, A. *et al.* Entrainment of neocortical neurons and gamma oscillations by the hippocampal theta rhythm. *Neuron* **60**, 683–697 (2008).
133. Seidenbecher, T., Laxmi, T. R., Stork, O. & Pape, H.-C. Amygdalar and hippocampal theta rhythm synchronization during fear memory retrieval. *Science* **301**, 846–850 (2003).
134. Lesting, J. *et al.* Directional theta coherence in prefrontal cortical to amygdalo-hippocampal pathways signals fear extinction. *PLoS One* **8**, e77707 (2013).
135. Schoenfeld, T. J. *et al.* Gap Junctions in the Ventral Hippocampal-Medial Prefrontal Pathway Are Involved in Anxiety Regulation. *J. Neurosci.* **34**, 15679–15688 (2014).
136. Adhikari, A., Topiwala, M. A. & Gordon, J. A. Single units in the medial prefrontal cortex with anxiety-related firing patterns are preferentially influenced by ventral hippocampal activity. *Neuron* **71**, 898–910 (2011).
137. Lesting, J. *et al.* Patterns of coupled theta activity in amygdala-hippocampal-prefrontal cortical circuits during fear extinction. *PLoS One* **6**, e21714 (2011).
- Initial investigation of the macrocircuit dynamics underlying fear learning, characterized by coordinated oscillatory activity among the amygdala, HPC, and PFC.**

138. Stujenske, J. M., Likhtik, E., Topiwala, M. A. & Gordon, J. A. Fear and safety engage competing patterns of theta-gamma coupling in the basolateral amygdala. *Neuron* **83**, 919–933 (2014).
139. Tejada, H. A. & O'Donnell, P. Amygdala Inputs to the Prefrontal Cortex Elicit Heterosynaptic Suppression of Hippocampal Inputs. *J. Neurosci.* **34**, 14365–14374 (2014).
140. Mogenson, G. J., Jones, D. L. & Yim, C. Y. From motivation to action: functional interface between the limbic system and the motor system. *Prog. Neurobiol.* **14**, 69–97 (1980).
141. Carvalho, M. C., Albrechet-Souza, L., Masson, S. & Brandão, M. L. Changes in the biogenic amine content of the prefrontal cortex, amygdala, dorsal hippocampus, and nucleus accumbens of rats submitted to single and repeated sessions of the elevated plus-maze test. *Braz. J. Med. Biol. Res. Rev. Bras. Pesqui. Médicas E Biológicas Soc. Bras. Biofísica A1* **38**, 1857–1866 (2005).
142. Collier, D. A. *et al.* A novel functional polymorphism within the promoter of the serotonin transporter gene: Possible role in susceptibility to affective disorders. *Mol. Psychiatry* **1**, 453–460 (1996).
143. Lesch, K.-P. *et al.* Association of anxiety-related traits with a polymorphism in the serotonin transporter gene regulatory region. *Science* **274**, 1527–1531 (1996).
144. Corbetta, M. & Shulman, G. L. Control of goal-directed and stimulus-driven attention in the brain. *Nat. Rev. Neurosci.* **3**, 201–215 (2002).
145. Houk, J. C., Adams, J. L. & Barto, A. G. in *Models of information processing in the basal ganglia* (eds. Houk, J. C., Davis, J. L. & Beiser, D. G.) 249–270 (MIT Press, 1995).
146. Joel, D., Niv, Y. & Ruppin, E. Actor-critic models of the basal ganglia: new anatomical and computational perspectives. *Neural Netw. Off. J. Int. Neural Netw. Soc.* **15**, 535–547 (2002).
147. Sugrue, L. P., Corrado, G. S. & Newsome, W. T. Choosing the greater of two goods: neural currencies for valuation and decision making. *Nat. Rev. Neurosci.* **6**, 363–375 (2005).
148. Nabavi, S. *et al.* Engineering a memory with LTD and LTP. *Nature* **511**, 348–352 (2014).

149. Butler, A. C., Chapman, J. E., Forman, E. M. & Beck, A. T. The empirical status of cognitive-behavioral therapy: a review of meta-analyses. *Clin. Psychol. Rev.* **26**, 17–31 (2006).
150. Sporns, O., Tononi, G. & Kötter, R. The human connectome: A structural description of the human brain. *PLoS Comput. Biol.* **1**, e42 (2005).



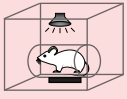


-  Anxiety medications
-  Blood pressure medications

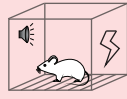
# Quantitative Assays of Emotional States in Rodents

Fear

Acoustic Startle Response



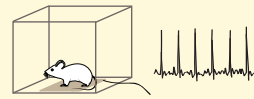
Pavlovian Fear Conditioning



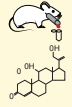
Anxiety

Stress

Vital Signs  
(i.e., heart rate, respiration rate, core temperature)



Plasma Hormones  
(i.e., glucocorticoids)



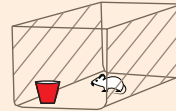
Ethological Tests  
(approach/avoidance conflict)

Active Avoidance

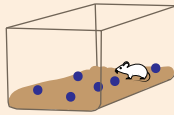
Hyperneophagia

Social Tests

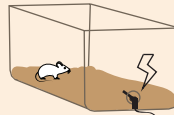
Novelty Suppressed Feeding



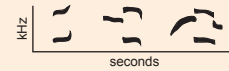
Marble Burying



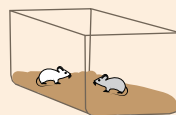
Shock Probe Burying



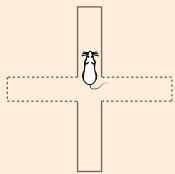
Ultrasonic Vocalizations



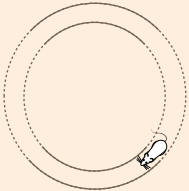
Social Interaction



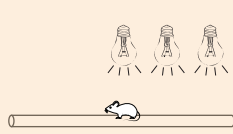
Elevated Plus Maze



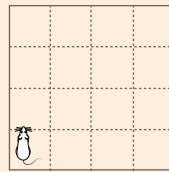
Elevated Zero Maze



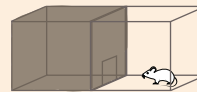
Elevated Alley (Suok Test)



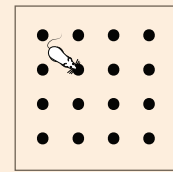
Open Field Test



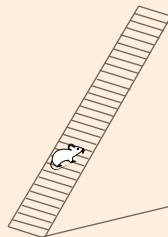
Light-dark Box



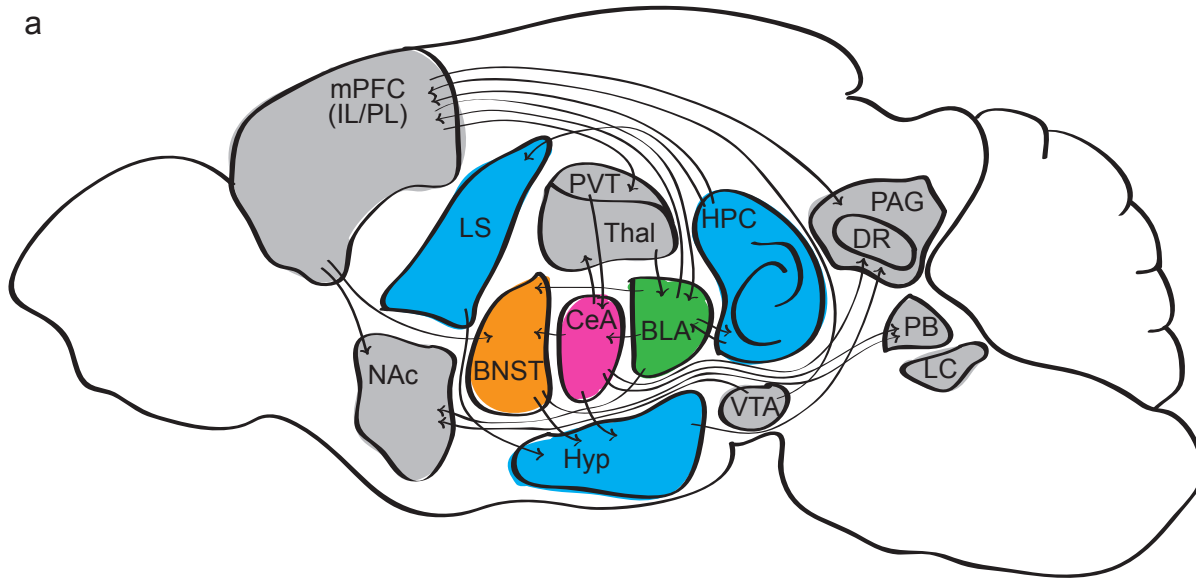
Hole Board



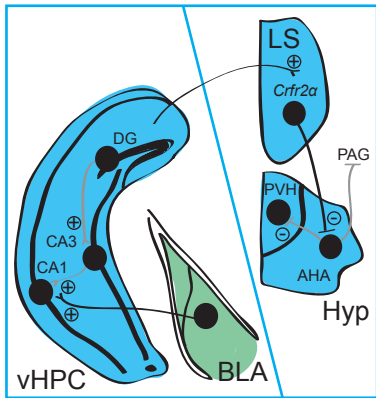
Staircase



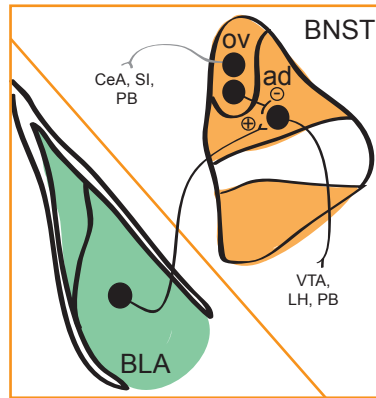
a



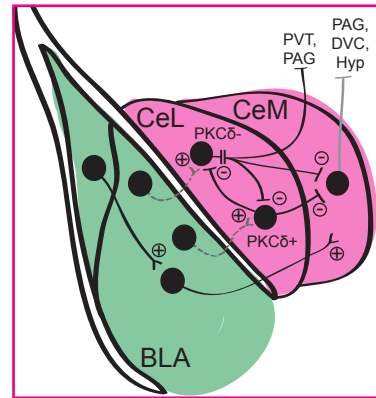
b



c

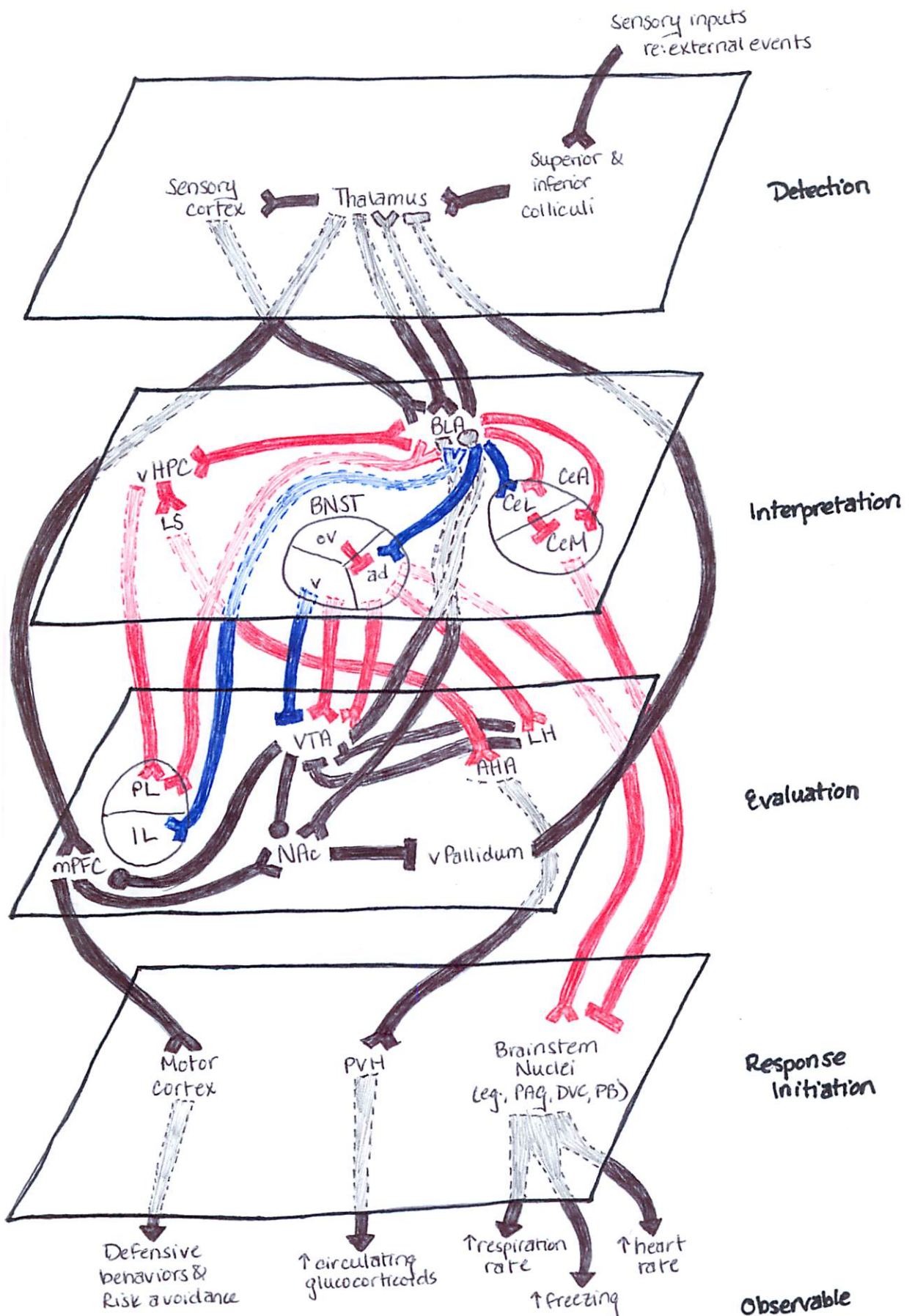


d



Legend (b-d)

- Projection confirmed with optogenetics
- Projection identified with other techniques
- - - Hypothetical projection



- Key**
- Excitatory Projection
  - ⊣ Inhibitory Projection
  - ⊙ Modulatory Projection
  - ➡ Anxiolytic Projection
  - ➡ Anxiogenic Projection

**Observable Response**