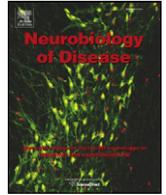




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Review

Losing your inhibition: Linking cortical GABAergic interneurons to schizophrenia

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ABSTRACT

GABAergic interneurons of the cerebral cortex (cINs) play crucial roles in many aspects of cortical function. The diverse types of cINs are classified into subgroups according to their morphology, intrinsic physiology, neurochemical markers and synaptic targeting. Recent advances in mouse genetics, imaging and electrophysiology techniques have greatly advanced our efforts to understand the role of normal cIN function and its dysfunction in neuropsychiatric disorders. In schizophrenia (SCZ), a wealth of data suggests that cIN function is perturbed and that interneuron dysfunction may underlie key symptoms of the disease. In this review, we discuss the link between cINs and SCZ, focusing on the evidence for GABAergic signaling deficits from both SCZ patients and mouse models.

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62

63 Introduction

64 Schizophrenia (SCZ) is a heterogeneous, heritable, neuropsychiatric
65 disorder that affects about 1% of the population worldwide. It is charac-
66 terized by positive symptoms (hallucinations and delusions), negative
67 symptoms (social withdrawal, avolition and anhedonia) and cognitive
68 symptoms (impairments in working memory, basic sensory processing
69 and higher order cognitive functions). Although the positive and nega-
70 tive symptoms are often the most striking features of the disease, the
71 cognitive defects lie at the core of the disorder and may precede the
72 development of other symptoms (Green, 2006; Keefe and Fenton,
73 2007; Lesh et al., 2011; Reichenberg et al., 2010; Walker et al., 1994).

74 One of the most prominent cognitive deficits observed in SCZ involves
75 working memory, an aspect of short-term memory by which information
76 is consciously maintained during the execution of other cognitive tasks.
77 An important aspect of working memory is the sustained firing of dorso-
78 lateral prefrontal cortex (DLPFC) pyramidal neurons between cue pre-
79 sentation and behavioral response (Funahashi et al., 1993). During this
80 period, GABAergic transmission is required for working memory, and in-
81 fusion of GABA antagonists into the DLPFC perturbs working memory by
82 disrupting the spatial tuning of these cells (Rao et al., 2000; Sawaguchi et
83 al., 1989).

84 Another cognitive deficit in SCZ patients is their inability to filter irrel-
85 evant sensory information (Javitt, 2009). A neurophysiological correlate
86 of this deficit is evaluated by a pre-attentive paradigm called paired
87 pulse inhibition (PPI). In PPI, subjects are presented a startling (test) stim-
88 ulus with or without a preceding non-startling (conditioning) stimulus.
89 In control subjects, the response to the test stimulus is suppressed by
90 the conditioned stimulus, but this suppression is reduced in SCZ subjects
91 (Freedman et al., 1996). Investigation of the neurophysiological correlates
92 of PPI identified a crucial role for GABAergic transmission through pre-
93 synaptic GABA_B receptors on glutamatergic terminals (Freedman et al.,
94 2000). Although deficits in neither PPI nor working memory are unique
95 to SCZ (Daskalakis et al., 2007), a detailed understanding of the physiolog-
96 ical basis for these cognitive functions would likely advance efforts to
97 improve therapies for SCZ.

98 Cognitive functions depend on the precise balance of excitatory
99 and inhibitory (E–I) activity of cortical circuits. Any alteration in the
100 E–I balance could perturb brain function unless there are compensatory
101 mechanisms to counteract this change. Much of the data presented in
102 this review supports the hypothesis that this E–I balance is altered in
103 SCZ. For example, a recent study used optogenetics to manipulate cortical
104 circuits and found that elevated excitation, but not elevated inhibition, in
105 neurons of the prefrontal cortex (PFC), leads to impaired cognition and
106 social behavior (Yizhar et al., 2011). Additionally, increasing inhibition
107 during elevated excitation, which likely restores the normal E–I balance,
108 reduced these behavioral deficits. Although it was not possible to directly
109 test disinhibition in this study, it is likely that deficits in GABAergic
110 transmission tip the E–I balance in the cortex. A gradual increase in
111 the E–I imbalance may occur in SCZ, which could eventually increase
112 the vulnerability of cortical circuits due to insufficiency of compensatory
113 mechanisms. Such a scenario is also consistent with the progressive
114 worsening of SCZ symptoms.

115 Cortical GABAergic neurotransmission plays a central role in control-
116 ling cognitive processes that are disrupted in SCZ. In this review, we dis-
117 cuss the recent evidence that links perturbations in GABAergic cortical
118 interneuron function to SCZ. We will summarize findings detailing the
119 deficits in neurochemical and synaptic markers in cINs from postmortem

120 SCZ tissue. Additionally, we will focus on several models that shed insight
121 into how cIN dysfunction could underlie many of the cognitive symptoms
122 associated with SCZ.

GABAergic interneurons of the cortex

123
124 In the cerebral cortex, the majority of GABAergic neurons are local
125 circuit neurons and referred to as cortical interneurons (cINs). cINs are
126 classified into subgroups and subtypes according to their morphology
127 (e.g. chandelier, martinotti, neurogliaform), intrinsic physiology
128 (e.g. fast-spiking, low threshold spiking), neurochemical markers and
129 their targeting of specific subcellular compartments (Ascoli et al., 2008).
130 Different forms of inhibition (tonic, feed-forward, feedback and shunting)
131 by distinct subtypes of cINs modulate cortical excitability and neuronal
132 plasticity (Daskalakis et al., 2007; Hensch, 2005).

133 Most cortical interneurons can be divided into three distinct sub-
134 groups based on several neurochemical markers: parvalbumin- (PV⁺),
135 somatostatin- (Sst⁺), or calretinin-expressing (CR⁺) interneurons, al-
136 though a small percentage of cINs express both CR and Sst. PV⁺ cINs
137 are fast-spiking (FS) and comprise two major subtypes: basket and chan-
138 delier cells. Basket cells can be divided into several subgroups morpholog-
139 ically while chandelier cells (ChCs) appear to be a homogeneous group
140 (Ascoli et al., 2008; Markram et al., 2004; Woodruff et al., 2011). Basket
141 cells primarily innervate the somata and proximal dendrites of pyramidal
142 neurons, as well as other interneurons, whereas chandelier cells selec-
143 tively target the axon initial segments of pyramidal neurons (AIS). Thus,
144 both basket and chandelier cells synapse near the site of action potential
145 initiation. Due to their rapid and non-accommodating spiking properties,
146 PV⁺ cINs are potent regulators of cortical circuits and could play impor-
147 tant roles in neurological diseases (Keefe and Fenton, 2007; Uhlhaas
148 and Singer, 2010; Uhlhaas et al., 2009; Woodruff et al., 2009, 2011).

149 The effect of GABAergic transmission depends on the postsynaptic
150 chloride equilibrium potential (E_{Cl^-}), since GABA receptors are permeable
151 to Cl⁻ and their reversal potential (E_{GABA}) is close to E_{Cl^-} . If E_{GABA} is more
152 negative than the resting membrane potential (V_{rest}) then it has a hyper-
153 polarizing (inhibitory) effect. If E_{GABA} is higher than V_{rest} then it has a
154 depolarizing (excitatory) effect. During development, intracellular Cl⁻ is
155 high due to relatively high levels of NKCC1 and low levels of KCC2,
156 co-transporters that uptake and extrude Cl⁻, respectively. Relative Cl⁻
157 concentration and E_{GABA} are also different in distinct subcellular neuronal
158 compartments, with lower Cl⁻ levels in dendrites and higher Cl⁻ levels
159 in AIS (Khirug et al., 2008). Hence, although basket cell synapses are
160 always inhibitory, the cortical axo-axonic synapses of ChCs can be
161 depolarizing (Khirug et al., 2008; Szabadics et al., 2006; Woodruff et al.,
162 2009). On the other hand, examination of ChC influence on pyramidal
163 neuron excitability, under conditions designed to mimic pyramidal neu-
164 ron activity in vivo, revealed an inhibitory effect (Woodruff et al., 2011).
165 In addition, GABAergic transmission at axo-axonic synapses of the hippo-
166 campus was reported to be hyperpolarizing (Glickfeld et al., 2009).

Cortical interneurons and brain oscillations in SCZ

167
168 There is extensive literature on the role of GABAergic transmission in
169 synchronization of network oscillations through electrical and synaptic
170 coupling of cINs (Beierlein et al., 2000; Moran and Hong, 2011;
171 Szabadics et al., 2001; Tamas et al., 2000; Uhlhaas and Singer, 2010).
172 This rhythmic inhibition synchronizes cortical circuits by generating a
173 narrow window for effective excitation. For example, Sst⁺ Martinotti

cells were reported to fire rhythmically at theta frequency (Fanselow et al., 2008) and neurogliaform cells were suggested to have the potential to shape cortical oscillations due to their extensive electrical coupling even with different subtypes of cINs (Simon et al., 2005). PV⁺ cINs can entrain gamma frequency oscillations via the combinatorial action of synaptic and electrical coupling (Bartos et al., 2002; Tamas et al., 2000), and loss of PV⁺ cells in the PFC correlates with reduced gamma-band response in a mouse model of SCZ (Lodge et al., 2009). Additionally, recent *in vivo* studies demonstrated that PV⁺ cIN driven gamma oscillations enhance responsiveness to sensory input (Cardin et al., 2009; Sohal et al., 2009).

Cortical EEG synchronization in response to a visual gestalt task increases dramatically during late adolescence (Uhlhaas et al., 2009), the time period when SCZ symptoms often manifest. Although EEG abnormalities have been reported in SCZ at all frequencies (Boutros et al., 2008; Cho et al., 2006; Moran and Hong, 2011; Siekmeier and Stufflebeam, 2010; Spencer et al., 2003, 2004; Sponheim et al., 1994), gamma frequency oscillations have attracted the most attention due to their association with cognitive functions that are commonly disrupted in SCZ, such as working memory and attention (Howard et al., 2003; Jefferys et al., 1996; Lisman and Idiart, 1995; Spencer, 2008; Steriade et al., 1996; Tallon-Baudry et al., 2005). These findings, together with the role of PV⁺ cINs in gamma oscillations and abnormalities observed at PV⁺ cIN synapses (see below), led to the hypothesis that cognitive dysfunction in SCZ may arise from abnormal cortical gamma oscillations due to deficiencies at PV⁺ cIN synapses (Lewis et al., 2012; Nakazawa et al., 2011; Uhlhaas and Singer, 2010).

So how does disinhibition affect gamma oscillations and cortical activity? One might expect reduced cIN activity to produce enhanced pyramidal neuron activity. Consistent with this idea, there is a robust enhancement of cerebral blood flow in the ventral hippocampus of SCZ patients, where a reduction of both PV⁺ and Sst⁺ cINs may be present (Konradi et al., 2011). This increased blood flow is thought to be secondary to enhanced pyramidal neuron activity (Schobel et al., 2009). Moreover, activity correlates with the degree of psychosis experienced, corroborating the importance of E–I balance for proper brain activity. SCZ has also been associated with “hypofrontality” during tasks requiring frontal activation (Glahn et al., 2005), albeit in the context of enhanced gamma power at baseline (pre-stimulus) conditions. It is conceivable that reduced activity of cINs could result in some basal increase in pyramidal neuron activity leading to an enhanced gamma power at baseline. However, the cIN deficit becomes functionally relevant when phase synchrony of gamma oscillations fail to occur normally during tasks that strongly engage the frontal cortex, resulting in reduced gamma stimulus-to-baseline ratios in SCZ (Gandal et al., 2012).

Deficits of cIN neurochemical subgroup markers in SCZ

Numerous studies have examined changes in neurochemical cIN markers and overall cIN numbers in postmortem SCZ brains, but there is often conflicting results. For example, despite the consensus that GAD67 mRNA levels are generally decreased in schizophrenic cortex, there is evidence both for (Konradi et al., 2011; Todtenkopf et al., 2005) and against (Akbarian et al., 1995; Hashimoto et al., 2003; Selemon et al., 1995; Thune et al., 2001; Woo et al., 1997) a reduction of cIN numbers. It is likely that methodological differences (i.e. marker used, controls for postmortem status, cortical region evaluated) underlie these conflicting data. Additionally, the tremendous genetic and diagnostic heterogeneity in SCZ minimizes the power to identify real differences in the context of relatively small sample sizes (generally less than 20 brains per group). Critical evaluation of the literature remains key to separating well-designed studies (preferably N = 10 or more brains for SCZ and control groups matched for age, sex, and post-mortem interval or brain pH; Table 1) from less complete studies. For example, one study reported an increase in PV⁺ interneurons in the cingulate cortex of SCZ brains (Kalus et al., 1997), which is in contrast to most of the literature.

In this study, the authors analyzed N = 5 SCZ and control brains, with a post-mortem interval averaging around 40 and 20 h for the SCZ individuals and controls, respectively. Such dramatic differences between groups can certainly introduce significant artifacts into the results.

In terms of neurochemically-defined interneuron subgroups, Sst mRNA is reduced in the DLPFC of SCZ patients, with some data supporting both a reduction in the total number of Sst⁺ cINs and Sst levels within individual cINs (Hashimoto et al., 2008a,b; Morris et al., 2008). Concurrently, there is a decrease in the expression of the Sst receptor subtype 2 (SSTR2) in pyramidal cells of SCZ patients (Beneyto et al., 2012). The specific Sst⁺ subtype that is affected, as well as a functional consequence for this decrease in Sst signaling, remains unclear.

Regarding the PV⁺ interneurons, there is mixed evidence regarding reductions of PV levels in SCZ patients. While some data supported a decrease in PV⁺ cells in SCZ patients (Beasley and Reynolds, 1997), others found similar densities of PV⁺ neurons in the DLPFC of SCZ and control patients (Beasley et al., 2002; Woo et al., 1997). At the same time, PV mRNA levels are diminished in the DLPFC of SCZ patients (Fung et al., 2010; Hashimoto et al., 2003, 2008b). As PV is an activity-regulated gene (Patz et al., 2004; Philpot et al., 1997), an intracellular reduction in PV could indicate a decrease in cIN activity and a potential shift in the E/I balance.

In contrast to the PV⁺ and Sst⁺ subgroups, the levels of CR mRNA and the density of CR⁺ neurons appears to be normal in SCZ tissue (Daviss and Lewis, 1995; Hashimoto et al., 2003; Woo et al., 1997). As most CR⁺ cINs have a distinct embryonic origin from the Sst⁺ and PV⁺ subgroups in rodents (Xu et al., 2004) and probably in humans (Fertuzinhos et al., 2009), the above results suggest that cINs derived from the medial ganglionic eminence may be most likely to be altered in SCZ. Given the evidence that ventral hippocampal overactivation may drive psychotic symptoms in SCZ (Schobel et al., 2009), it would be interesting to see if other groups can replicate the recent finding of a reduction in PV⁺ and Sst⁺ cINs in the hippocampus (Konradi et al., 2011).

Synaptic deficits of cINs in SCZ

Evidence for the role of GABAergic neurotransmission in the cognitive functions that are impaired in SCZ led researchers to examine the components of GABA signaling (Table 1). Several studies performed DNA microarray analyses to identify large populations of genes whose expression was altered in the DLPFC of SCZ patients (Hashimoto et al., 2008a; Mirnics et al., 2000; Vawter et al., 2002) whereas other studies were based on candidate gene approaches. Identifying genes and genomic regions that underlie the pathogenesis of SCZ has been a formidable challenge. Initial linkage studies identified numerous loci that were linked with SCZ, but only a few of these regions were successfully replicated (several of which are discussed below). A series of genome-wide association studies failed to identify any clear SCZ susceptibility alleles, while many studies examining copy number variations and *de novo* mutations have provided little insight (reviewed in (Girard et al., 2012)). There appears to be significant genetic heterogeneity in SCZ, which presents a major challenge for developing genetic models of SCZ and linking these findings with human disease. Here we will focus on several candidate genes and mechanisms that appear to be associated with defects cIN synaptic transmission defects in SCZ.

Deficits at input synapses onto cINs

NMDA receptor hypofunction

N-Methyl-D-aspartic acid (NMDA) receptors (NMDARs) are molecular coincidence detectors that are only active when the synaptic membrane is depolarized and glutamate is bound to the receptor. Activation and opening of NMDARs leads to an influx of Ca²⁺, which can activate many downstream signaling cascades. One important function of NMDAR activation is the regulation of AMPA receptor

Table 1
 Summary of the molecular deficits in cINs found in SCZ patients and the phenotypes observed. Only postmortem studies that included ≥ 10 SCZ and age-matched control brains are included in the table. All postmortem studies controlled for postmortem interval, brain pH or both between SCZ and control subjects. All measurements of mRNA and/or protein were taken from the prefrontal cortex of postmortem brains (specifically Brodmann's areas 9, 10 or 46) unless indicated below. * Konradi et al., 2011 – only examined the hippocampus. ** Hashimoto et al., 2008 – also examined anterior cingulate, M1 and V1. *** Guidotti et al., 2000 – also examined cerebellum. **** Thompson et al., 2009 – examined PFC and other cortical areas, as well as striatum and thalamus. Chandelier cell, ChC; pyramidal cell, PC; basket cell, BC.

	GABAergic cIN deficits	mRNA/protein	Post-mortem SCZ brains	Linkage studies	Behavioral phenotype	Biochemical phenotype	Physiological phenotype
t1.7	cIN subgroup markers	↓Parvalbumin	Beasley et al., 2002; Hashimoto et al., 2003; Konradi et al., 2011*				
t1.8		↓Somatostatin	Hashimoto et al., 2008a,b**; Konradi et al., 2011*; Morris et al., 2008				
Q3 t1.10	Input synapses (presynaptic changes)	Neuregulin	↑Chong et al., 2008; Hashimoto et al., 2004; Law et al., 2006 ↓Bertram et al., 2007	Harrison et al., 2006; Mei et al., 2008; Stefansson et al., 2002; Walss-Bass et al., 2006	Chen et al., 2008b; Deakin et al., 2009; Duffy et al., 2010; Ehrlichman et al., 2009; Karl et al., 2007; Kato et al., 2010; O'Tuathaigh et al., 2007, 2008, 2010; Stefansson et al., 2002 Belforte et al., 2010; Korotkova et al., 2010	Fazzari et al., 2010; Hahn et al., 2006; Shibuya et al., 2010	Chen et al., 2010a
Q4							
Q5							
t1.11	Input synapses (postsynaptic changes)	↓NMDAR					
Q6							
t1.12		ErbB4	↑Chong et al., 2008; Law et al., 2007	Benzel et al., 2007; Nicodemus et al., 2006; Norton et al., 2006; Silberberg et al., 2006; Walsh et al., 2008	Barros et al., 2009; Chen et al., 2010b; Fazzari et al., 2010; Golub et al., 2004; Stefansson et al., 2002; Wen et al., 2010;	Hahn et al., 2006	Barros et al., 2009; Chen et al., 2010b; Fazzari et al., 2010; Wen et al., 2010;
Q7							
t1.13	Output synapses (presynaptic changes)	↓GAD67 in PV ⁺ cINs	Akbarian et al., 1995; Curley et al., 2011; Guidotti et al., 2000***; Hashimoto et al., 2003, 2008a,b**; Thompson et al., 2009****; Volk et al., 2000				
t1.14		↓GAT1 in ChC	Pierri et al., 1999; Volk et al., 2001; Woo et al., 1998				
Q8 t1.15	Output synapses (postsynaptic changes)	↓GABA _A α1 at BC synapses onto PC	Beneyto et al., 2011; Glausier et al., 2011; Hashimoto et al., 2008a,b**				
t1.16		↑GABA _A α2 at ChC synapses onto PC	Beneyto et al., 2011; Volk et al., 2002;				

trafficking, which plays a major role in synaptic plasticity. NMDARs are important mediators of various forms of synaptic plasticity, such as spike-timing dependent plasticity (STDP), long-term potentiation (LTP) and long-term depression (LTD). NMDAR-dependent plasticity plays a major role in learning and memory (Takahashi et al., 2003) and synapse formation (Inan and Crair, 2007; Lamsa et al., 2010). Synaptic plasticity can be induced at glutamatergic synapses on to cINs as well as at GABAergic synapses, but the form of synaptic plasticity at these synapses is specific to the brain region and cIN subtype (Kullmann and Lamsa, 2011; Lamsa et al., 2010).

The theory of NMDA receptor (NMDAR) hypofunction as a root cause of SCZ has been a long-standing hypothesis since phencyclidine (PCP), a drug that induces SCZ-like symptoms, was found to be a non-competitive NMDAR antagonist (Lodge and Anis, 1982). Administration of NMDAR antagonists such as PCP, ketamine and MK801 results in cortical excitatory neuron hyperactivation (Jackson et al., 2004; Krystal et al., 1994; Suzuki et al., 2002) and decreased GAD67 and PV expression in cINs (Behrens et al., 2007; Cochran et al., 2003; Gietl et al., 2007; Keilhoff et al., 2004; Kinney et al., 2006; Morrow et al., 2007; Rujescu et al., 2006). This excitatory neuron hyperactivation is possibly due to disinhibition of excitatory neurons via NMDAR hypofunction in cINs (Homayoun and Moghaddam, 2007). Additionally, the density of cINs (specifically PV⁺ cINs) expressing the NR2A subunit of NMDAR is notably reduced in SCZ brains (Bitanirhwre et al., 2009; Woo et al., 2004, 2008). Furthermore, transplantation of cIN progenitor cells can prevent the induction of PCP-induced cognitive defects (Tanaka et al., 2011). These studies led to the hypothesis that NMDAR hypofunction in GABAergic interneurons contributes to excitatory neuron hyperexcitability in the etiology of SCZ-like symptoms (Fig. 1).

Compelling evidence exists for NMDAR hypofunction in PV⁺ cINs contributing to hyperactivity in DLPFC excitatory neurons. However, NMDAR-mediated synaptic currents appear to decrease in PV⁺ cINs with age (Rotaru et al., 2011; Wang and Gao, 2009, 2010). Thus, it is unclear how NMDAR hypofunction in PV⁺ cINs would manifest into a later-developing disease like SCZ, when NMDAR-mediated currents are already low in these neurons at this stage of development. A recent study may explain this conflict with the finding that prolonged exposure of MK801 leads to a reduction in the amplitude of AMPAR-mediated synaptic currents in FS PV⁺ cINs but an increase in the amplitude of AMPAR-mediated synaptic currents in pyramidal cells (Wang and Gao, 2012). Hence, early NMDAR hypofunction may lead to a reduction in AMPA-mediated synaptic currents specifically in FS cINs, possibly through an LTD-like mechanism, although an NMDAR-dependent LTD is yet to be shown at these synapses. Reduced activation of FS cINs could lead to disinhibition of pyramidal cells resulting in an increase in AMPAR-mediated synaptic currents during basal synaptic transmission.

On the other hand, MK801 also induced an increase in the frequency of AMPAR-mediated currents in DLPFC pyramidal cells but not in FS PV⁺ cINs. Furthermore, the addition of new presynaptic NMDARs is observed in axon terminals targeting pyramidal cells but not FS PV⁺ cINs (Wang and Gao, 2012). Since presynaptic NMDARs can facilitate glutamate release (Corlew et al., 2008), this mechanism likely explains the observation of increased frequency of AMPAR-mediated synaptic currents of pyramidal cells and not that of FS PV⁺ cINs. Hence, consistent with earlier findings, this study provided a plausible mechanism on how chronic MK801 treatment can have opposing effects on these two cell types: reduction of FS cIN activity via decreased AMPAR-mediated currents while hyperactivation of pyramidal cells by increased glutamate

358 release and reduced inhibition. These findings provide a clearer explanation
 359 by which NMDAR hypofunction could induce distinct processes at
 360 different synapses to underlie the complex SCZ pathophysiology. Additional
 361 support for this mechanism could be obtained by determining if
 362 other NMDAR antagonists such as PCP or ketamine can replicate these
 363 findings.

364 In order to better tease apart NMDAR function and its relation to
 365 SCZ in different cell types, several groups disrupted NMDAR function
 366 specifically in a subset of GABAergic cINs. Removal of the NR1 subunit
 367 (the mandatory subunit for NMDAR function) in ~50% of cINs, the
 368 majority of which were PV⁺, during the second postnatal week led
 369 to behavioral phenotypes similar to the symptoms observed in SCZ
 370 patients such as hyperactivity, increased anxiety, and perturbations in
 371 working memory and PPI (Belforte et al., 2010). NR1-null cINs contained
 372 reduced levels of GAD67 and PV, and excitatory neurons displayed
 373 increased firing rates, which are possibly due to disinhibition. These
 374 findings are consistent with activity-dependent PV expression and
 375 they suggest that NMDAR-dependent activity is upstream of GABAergic

376 transmission in this model. Furthermore, ablation of NMDAR function
 377 in cINs at a later age (~8 weeks old, which corresponds to
 378 post-adolescence) did not reveal any SCZ-like behavioral phenotype.
 379 These findings suggest a crucial role for intact NMDAR function in cINs
 380 during early development.

381 Two other groups utilized a PV-Cre mouse line to remove NR1 in
 382 PV⁺ cINs and found that these mice have impairments in gamma oscillations
 383 and in spatial and working memory tasks (Carlen et al., 2012;
 384 Korotkova et al., 2010). In contrast to the previous study, these groups
 385 did not observe abnormal social behavior, which may be due to the
 386 relatively later knockout of NMDAR function in PV-Cre mice (3rd postnatal
 387 week), again emphasizing the developmental role of NMDAR function
 388 in these cINs.

389 These studies addressing the role of NMDAR hypofunction in FS
 390 PV⁺ cINs have several caveats. First, the phenotypes analyzed are
 391 not symptoms unique to SCZ, making it difficult to draw clear connections
 392 between the observed findings and SCZ. Second, these studies
 393 either do not specifically ablate NMDARs only from FS PV⁺ cINs, or

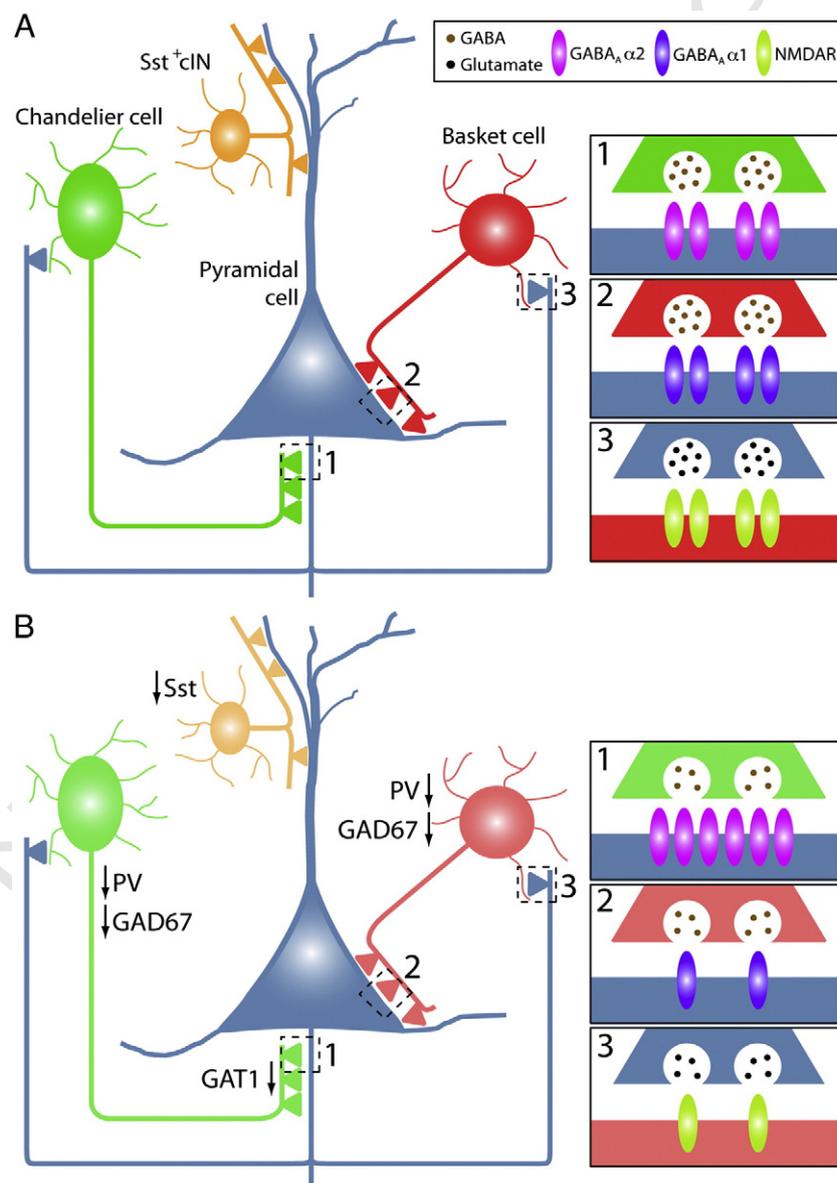


Fig. 1. Schematic depicting a simplified cortical circuit (A) and some of the cortical interneuron (cIN)-related changes that are reported in SCZ patients (B). Sst, PV, GAD67 and GAT1 expression are reduced in SCZ patients. Postmortem studies reveal an increase in GABA_A α2 receptors at chandelier cell synapses onto pyramidal cells (1), a decrease in GABA_A α1 receptors at basket cell synapses onto pyramidal cells (2), and a decrease of NMDA receptors (NR2A subunit, in particular) at excitatory synapses onto PV⁺ cINs (3). Although only pyramidal synapses onto basket cells are shown, the reduction of NMDA receptors may also occur at synapses onto chandelier cells.

they ablate NMDARs in FS cINs at a relatively late developmental stage. Third, studies using NMDAR antagonists to model SCZ inhibit NMDARs throughout the brain, making it difficult to correlate site of action with phenotype. Future studies are needed to ablate NMDARs specifically in FS PV⁺ cINs early during development to determine if NMDA hypo-function in PV cells is sufficient to produce SCZ-like symptoms. While this aim will be aided by the recent production of many cIN subtype-specific Cre lines (Taniguchi et al., 2011), an early marker of PV-fated cINs is still unknown. Another beneficial approach would be to analyze whether animal models that better mimic mutations identified in genetic linkage studies, such as 22q11.2 or ErbB4 deletion models (see below), have NMDAR deficits in their FS PV⁺ cINs.

Perturbation in Neuregulin1/ErbB4 signaling

One of the replicated hits from linkage studies was located on chromosome 8p. Extensive haplotype analysis from several Icelandic SCZ families identified a series of SNPs and microsatellites within the 5' through the second intron of the *Nrg1*, making *Nrg1* a candidate SCZ susceptibility gene (Stefansson et al., 2002). Additional studies have found genetic associations between *Nrg1* and SCZ in multiple affected populations (Harrison and Law, 2006; Mei and Xiong, 2008).

Neuregulins are trophic growth factors that stimulate ErbB receptor tyrosine kinases. There are four different Neuregulin genes, with Neuregulin1 (*Nrg1*) being the best characterized and most prominent in the developing and adult brain. Although there are multiple ErbB receptors, ErbB4 is the only autonomous *Nrg1*-specific receptor that becomes catalytically active upon *Nrg1* interaction. Numerous studies identified *ErbB4* as a candidate susceptibility gene for SCZ (Benzel et al., 2007; Nicodemus et al., 2006; Norton et al., 2006; Silberberg et al., 2006; Walsh et al., 2008). The *Nrg1*–*ErbB4* interaction plays a prominent role in many aspects of neuronal development, including neuronal migration, axon guidance and synapse formation and plasticity (Mei and Xiong, 2008; Rico and Marín, 2011).

Most SNPs for *Nrg1* and *ErbB4* are found in non-coding regions (introns, 5' or 3' sequences), making it unclear how these SNPs regulate gene expression or function. There are conflicting reports for both an increase (Chong et al., 2008; Hashimoto et al., 2004; Law et al., 2006) and decrease (Bertram et al., 2007) of *Nrg1* mRNA in the PFC cortex and hippocampus of SCZ postmortem brains. Although the levels of *Nrg1* protein in the brain of SCZ patients remain unknown, *Nrg1* levels are decreased in the serum of SCZ patients compared to controls (Shibuya et al., 2011). Additionally, some isoforms of the *ErbB4* mRNA were also increased in SCZ brains (Law et al., 2007; Silberberg et al., 2006), and there is some evidence for increased expression of *Nrg1* and *ErbB4* protein in the DLPFC of SCZ patients (Chong et al., 2008). Another study reported that the expression levels of *Nrg1* and *ErbB4* are similar between SCZ postmortem tissue and controls, but there is an increase in *Nrg1*-induced *ErbB4* activation and increases in *ErbB4*–PSD95 interactions (Hahn et al., 2006).

Until recently, the cellular localization of *ErbB4* in the cortex was controversial, with the predominant view being that *Nrg1*/*ErbB4* signaling functioned at excitatory synapses. However, several recent studies have demonstrated that *ErbB4* is largely restricted to PV⁺ GABAergic interneurons in the murine cortex and hippocampus, with limited (if any) expression in projection neurons or Sst⁺ interneurons (Fazzari et al., 2010; Neddens and Buonanno, 2010; Vullhorst et al., 2009; Woo et al., 2007). Specifically, *ErbB4* was present in the postsynaptic densities of PV⁺ cINs receiving glutamatergic inputs and the presynaptic axon terminals of both basket cells and chandelier cell cartridges. This *Nrg1*–*ErbB4* interaction regulates synapse formation and GABAergic transmission (Woo et al., 2007). In addition, there is some evidence that this *ErbB4* expression pattern is conserved in higher mammals (Neddens et al., 2011).

Nrg1 and *ErbB4* knockout mice die during embryogenesis, so the initial data obtained from mouse models came from heterozygous or hypomorphic mice. *Nrg1* mutant mice display impairments in behavioral

tasks that are relevant to the negative and cognitive symptoms of SCZ, such as decreased PPI, hyperexcitability, and perturbations in social interactions and fear conditioning (Duffy et al., 2010; Ehrlichman et al., 2009; Karl et al., 2007; O'Tuathaigh et al., 2007, 2008, 2010; Stefansson et al., 2002). Spatial and working memory remains intact in these mice, but mice with specific mutations of Type III *Nrg1* did show evidence of impaired working memory (Chen et al., 2008b). Surprisingly, overexpression of *Nrg1* also increased locomotor activity, reduced PPI and perturbed fear conditioning and social interactions (Deakin et al., 2009; Kato et al., 2010). Restricted *Nrg1* overexpression in individual pyramidal neurons greatly enhanced the number of GAD65⁺ boutons targeting somata and AIS (likely basket and chandelier cells, respectively) (Fazzari et al., 2010).

ErbB4 mutant mice also display increased hyperactivity, impaired working memory and decreased PPI (albeit to a lesser extent compared to *Nrg1* mutants) (Barros et al., 2009; Golub et al., 2004; Stefansson et al., 2002). The discovery of *ErbB4* restriction to PV⁺ cINs has allowed researchers to knockout *ErbB4* specifically in these cells to better characterize its function in cINs. Early disruption of *ErbB4* using GFAP-Cre or *Dlx5/6*-Cre mice decreased excitatory synapses, overall spine number, the number of chandelier synapses, synaptic transmission between cINs and projection neurons, and impaired PPI (Barros et al., 2009; Fazzari et al., 2010). Elimination of *ErbB4* with PV-Cre decreased GABAergic transmission, induced locomotor hyperactivity, and caused impairments in PPI, working memory and fear conditioning (Chen et al., 2010b; Wen et al., 2010).

These studies outline the function *Nrg1*–*ErbB4* in cIN synaptic transmission and demonstrate that perturbations in this signaling system induce cellular and behavioral changes that are consistent with a SCZ phenotype. However, since SCZ-associated *Nrg1* and *ErbB4* SNPs are generally restricted to non-coding regions (but see (Walsh-Bass et al., 2006; Walsh et al., 2008)), it will be interesting to determine whether *Nrg1* or *ErbB4* mouse models that better mimic SCZ-associated SNPs induce similar effects as the above studies (Chen et al., 2010a).

Deficits at output synapses of cINs

Presynaptic defects

Glutamate is converted to GABA via two isoforms of glutamic acid decarboxylase (GAD), GAD65 and GAD67. Numerous postmortem studies have found that GAD67 mRNA (Akbarian et al., 1995; Volk et al., 2000) and protein (Curley et al., 2011; Guidotti et al., 2000) are decreased in a subset (~25–35%) of DLPFC interneurons in SCZ patients, whereas GAD65 expression is largely intact in these brains (Benes et al., 2000; Guidotti et al., 2000). Further studies found that the loss of GAD67 mRNA and protein was restricted to PV⁺ cells, with nearly 50% of PV⁺ cINs in the PFC of SCZ patients lacking GAD67 expression (Curley et al., 2011; Hashimoto et al., 2003). It appears that reduced GAD67 levels are present in basket cells (Fig. 1), since decreased GAD67 protein was observed in non-chandelier PV⁺ axon terminals (Curley et al., 2011), but more definitive data on the cIN subtype distribution of decreased GAD67 levels in SCZ is needed. GAD67 expression is also decreased in other cortical regions of SCZ patients (Hashimoto et al., 2008b; Thompson et al., 2009), indicating that this defect is not specific to GABAergic DLPFC cINs. Of note, a decrease in GAD67 does not necessarily indicate a decrease in GABA levels, and attempts at measuring GABA levels in SCZ patients has produced conflicting results (Goto et al., 2009; Ongur et al., 2010). However, GAD67 is activity regulated (Benson et al., 1994), indicating that cells with a reduction in GAD67 level may be firing less than normal. These findings suggest that there is a reduction in GABAergic neurotransmission in PV⁺ cINs of SCZ patients, which could lead to disinhibition of cortical excitatory neurons.

In addition to GAD67, expression of the GABA membrane transporter 1 (GAT1), which is involved in the reuptake of GABA, is reduced in a subset of cINs in the PFC of SCZ patients (Ohnuma et al., 1999; Volk et al., 2001). Several studies utilized GAT1 staining of chandelier cell cartridges

to identify a decrease in the density of GAT1⁺ cartridges in the PFC of SCZ patients (Fig. 1) (Pierri et al., 1999; Woo et al., 1998). It remains unclear whether these findings reflect a decrease in GAT1 levels with normal cartridge numbers, or a decrease in the number of cartridges in SCZ patients. Interestingly, the density of non-chandelier GAT1⁺ terminals was unchanged in SCZ patients. Similar to GAD67, the exact distribution of decreased GAT1 levels between basket and chandelier cells is unknown and requires further study.

Postsynaptic defects

Two prominent GABA_A receptor subunits have been examined in SCZ patients: GABA_A α1 receptors are postsynaptic to basket cell synapses on pyramidal neuron cell bodies and proximal dendrites, whereas GABA_A α2 receptors are primarily postsynaptic to chandelier cells on the AIS of pyramidal neurons. Several studies have identified a decrease in GABA_A α1 receptor mRNA in the DLPFC cortex of SCZ patients (Beneyto et al., 2011; Hashimoto et al., 2008a,b), with some evidence that the decrease is specific to pyramidal cells (Fig. 1) (Glausier and Lewis, 2011). These findings suggest that inhibition is reduced at basket cell synapses on pyramidal neurons. Consistent with this idea, two kinases that differentially modulate the chloride ion transporters NKCC1 and KCC2 were found to be elevated in the DLPFC of SCZ patients (Arion and Lewis, 2011). Enhanced activation of NKCC1 relative to KCC2 would be expected to increase intracellular chloride levels and thus diminish GABA-mediated inhibition of pyramidal neurons. These molecular deficits are consistent with the neurophysiological defects observed for cortical inhibition in SCZ patients (Daskalakis et al., 2007) as well as the disinhibition hypothesis of excitatory neurons in SCZ. Recently, such a reduction in inhibition at basket cell synapses was proposed to be a homeostatic response to the pyramidal neuron's receiving decreased excitatory inputs in SCZ (Lewis et al., 2012).

GABA_A α2 receptor protein (Volk et al., 2002) and mRNA (Beneyto et al., 2011) expression is increased in the PFC of SCZ patients compared to controls, with a clear enrichment of GABA_A α2 receptor protein at the AIS (Fig. 1). Both the decrease in GAT1 in chandelier cartridges and the increase in postsynaptic GABA_A α2 receptors were suggested to be compensatory mechanisms to enhance GABA transmission at the axo-axonic synapses of SCZ patients (Lewis et al., 2012).

The role of cINs in other SCZ models

In addition the models described above, there are other SCZ-associated genes that have received significant attention. Here we describe several SCZ mouse models in which cIN function is beginning to be examined.

Dysbindin and clathrin-mediated endocytosis

Dysbindin-1 is encoded by dystrobrevin-binding protein 1 gene (DTNBP1) located at chromosome 6p22.3. SNP and haplotype analyses of the DTNBP1 locus of SCZ patients from multiple populations found linkage between DTNBP1 and SCZ, making dysbindin a potential SCZ susceptibility gene (Rethelyi et al., 2010; Riley et al., 2009; Talbot et al., 2009; Zuo et al., 2009). DTNBP1 gene variations were also shown to influence cognitive functions related to the PFC (Burdick et al., 2006; Fallgatter et al., 2006). DTNBP1 haplotypes with increased protein expression are associated with enhanced working memory performance (Wolf et al., 2011). On the other hand, risk haplotypes of DTNBP1 are associated with reduced spatial memory (Donohoe et al., 2007). Dysbindin-1 is found at both pre-synaptic and postsynaptic sites of glutamatergic synapses (Talbot et al., 2006), and it is found to be reduced in the hippocampus and PFC of SCZ brains (Talbot et al., 2004, 2011; Tang et al., 2009a).

Dysbindin-1 regulates biogenesis of lysosome-related organelles and is involved in protein trafficking through the lysosomal pathway. Receptor trafficking is mediated by recycling endosomes or clathrin-mediated endocytosis (CME), which targets proteins to lysosomes for degradation.

Alteration in Dysbindin-1 expression was found to affect surface expression of the D2 subunit of dopamine receptors, as well as NR1 and NR2A subunits of NMDAR, all of which are trafficked via CME (Jeans et al., 2011; Ji et al., 2009; Karlsgodt et al., 2011; Schubert et al., 2011; Tang et al., 2009b). Consistent with its role in NMDAR trafficking, Dysbindin-1 knockout mice (Dys^{-/-}) have altered NMDAR-mediated currents and synaptic plasticity. Of note, loss of Dysbindin-1 was found to have differential effects on the NMDAR-mediated currents at hippocampal and PFC glutamatergic synapses, which may be due to differential regulation of distinct NMDAR subunits (Jentsch et al., 2009; Ji et al., 2009; Karlsgodt et al., 2011; Tang et al., 2009b).

Dys^{-/-} mice also display deficits in spatial working memory and PPI, increased locomotion, impaired gamma-band oscillations, and reduced inhibition in the hippocampus with no change in excitation (Carlson et al., 2011; Jentsch et al., 2009; Karlsgodt et al., 2011). One group observed a reduction in the number of PV⁺ cells in the hippocampus (Carlson et al., 2011). Dys^{-/-} mice also have reduced inhibition of layer V PFC pyramidal neurons, possibly due to decreased excitability of FS cINs (Ji et al., 2009). Deficits in dysbindin-1 mutants may not be restricted to the postsynaptic side. In the Sandy mouse (*Sdy*), an inbred line carrying a spontaneous mutation in *dysbindin-1*, larger vesicle size and reduced readily releasable pool of synaptic vesicles were detected (Chen et al., 2008a).

In sum, by regulating multiple neurotransmitter systems on both sides of the synapse, dysbindin-1 function may be relevant for multiple aspects of synaptic activity and SCZ pathophysiology. However, further analysis is necessary to understand the molecular basis of this regulation. Finally, although Dysbindin-1 was detected at glutamatergic synapses of the hippocampus, its presence at GABAergic synapses of the cortex is still unclear. Since GABA receptor subunits are trafficked to the postsynaptic membrane via CME (Tretter and Moss, 2008), it is also possible that Dysbindin-1 regulates the surface expression of GABA receptors.

Disrupted in Schizophrenia-1 (*DISC1*)

A truncating mutation in the *Disrupted in Schizophrenia-1* (*DISC1*) gene was first identified in a Scottish family with a high incidence of psychiatric disorders including SCZ, depression and anxiety diseases (Blackwood et al., 2001; Millar et al., 2000; St Clair et al., 1990). Although many independent genetic linkage and association studies support a linkage between *DISC1* and psychiatric illnesses, there is significant controversy whether a specific linkage between *DISC1* and SCZ actually exists (Kvajo et al., 2011b). *DISC1* encodes a large protein with relatively little sequence homology to other known genes, hampering progress for identifying a clear function for *DISC1*. Despite these drawbacks, *DISC1* has been shown to play a role in neuronal cell proliferation, maturation, migration, neuronal plasticity, and regulation of numerous intracellular signaling cascades (Singh et al., 2011; Soares et al., 2011). However, these studies used knockdown or overexpression approaches to study *DISC1* function in a manner that does not model the susceptibility allele. In fact, many of these migration and maturation defects were not observed in a mouse model with a truncating lesion in the *Disc1* gene that mimics the mutation in the Scottish family (Kvajo et al., 2008, 2011a), highlighting the importance for creating transgenic mice that best recapitulate the human SCZ-related genetic mutations.

Eight distinct *DISC1* mutant mice have been reported, several of which display some SCZ symptoms, such as impairments in working memory and deficits in PPI (Kelly and Brandon, 2011). In several mouse models that overexpress a truncated version *DISC1*, PV immunoreactivity was decreased in the medial PFC compared to controls (Ayhan et al., 2011; Hikida et al., 2007; Shen et al., 2008). There was no decrease in either calretinin or calbindin in *Disc1* mutant mice. Of note, although there was no reduction of PV⁺ cells in the DLPFC, the laminar organization of PV⁺ cells was perturbed (Shen et al., 2008). However, no changes in the number of PV⁺ or calbindin⁺ cINs were detected in a mouse model that mimics the *Disc1* allele from the Scottish family (Kvajo et al., 2008). shRNA-mediated knockdown of *Disc1* in pyramidal cells of the prefrontal

cortex also led to a reduction in PV⁺ cells in this area, indicating that the decrease in PV⁺ interneurons could be non-autonomous (Niwa et al., 2010). Recent evidence indicates that Disc1 may regulate dendritic growth during periods of prolonged GABA-mediated depolarization in hippocampal neurogenesis (Kim et al., 2012). It also appears that DISC1 functions in cIN tangential migration (Steinecke et al., 2012). Future studies are needed to link dysfunction of Disc1-containing risk alleles to the specific pathobiology of SCZ.

22q11.2 deletion syndrome (22qDS)

One known genetic factor underlying the risk of developing SCZ is the microdeletion in the chromosomal region 22q11.2, which occurs in roughly 1 in 3000 births and leads to the 22q deletion syndrome (22qDS, DiGeorge syndrome, velocardiofacial syndrome) (Shprintzen et al., 2005). 22qDS patients display impairments in a variety of cognitive tasks (Karayiorgou et al., 2010), and roughly 30% of carriers with this deletion are diagnosed with SCZ (Murphy et al., 1999; Pulver et al., 1994), such that this mutation constitutes approximately 1–2% of the sporadic cases of SCZ (Bassett et al., 2008; Xu et al., 2008). The size of the microdeletion is either 1.5 Mb or 3 Mb, and both deletions are associated with a higher risk of SCZ (Karayiorgou et al., 1995). The 1.5 Mb region contains 27 functional genes (Edelmann et al., 1999) whose dosage reductions are proposed to have adverse effects on early patterning, neurogenesis and synaptogenesis (Meechan et al., 2011). In mice, orthologues of 26 of these genes are located on chromosome 16, although the gene order is slightly different (Maynard et al., 2006; Puech et al., 1997).

Among several mouse lines with different chromosome 16 deletions, two lines, Df(16A^{+/-}) and Lgd1, carry a deletion in chromosome 16 that is syntenic to the 1.5 Mb microdeletion of the human chromosome 22q11.2 (Meechan et al., 2006; Stark et al., 2008). Both Df(16A^{+/-}) and Lgd1 display impaired PPI, but only Df(16A^{+/-}) mice have conditioned fear and spatial working memory deficits (Long et al., 2006; Stark et al., 2008). Analyses of network oscillations during a working memory task, in which Df(16A^{+/-}) mice show impairments, revealed reduced synchrony of hippocampal and PFC oscillations (Sigurdsson et al., 2010). Whether the underlying pathophysiology of hippocampal-cortical oscillation synchrony in Df(16A^{+/-}) mice involves cINs is not clear. However, inhibition of pyramidal neurons in the CA1 region of the hippocampus is also reduced in Df(16A^{+/-}) mice (Drew et al., 2011b). Lgd1 mice display alterations in PV⁺ cIN layer distribution and cIN migration deficits, although the total number of PV⁺ cINs is not changed (Meechan et al., 2009). A recent study found that cIN migration and lamination defects in Lgd1 mice might be caused by disruption of C-X-C chemokine receptor type 4 (Cxcr4) signaling (Meechan et al., 2012), a well-characterized guidance mechanism required for proper cIN migration (Wang et al., 2011). Thus, unlike several of the mouse models mentioned above, Df(16A^{+/-}) and Lgd1 mice may provide a more accurate model of the human 22q deletion, though the extent to which these mice recapitulate SCZ symptoms is still under investigation (Drew et al., 2011a).

Interneuron dysfunction in SCZ: cause or effect?

The evidence for various input and output-related deficits in cINs from SCZ studies begs the question of whether cIN alterations could be an effect, rather than a cause, of the core SCZ pathology. A wealth of data from imaging studies suggest that SCZ is associated with reduced gray matter thickness that is present early in the illness. Postmortem studies suggest that the volume loss mainly results from a reduction in neuropil and not cells (Selemon et al., 1995; Thune et al., 2001). Several lines of evidence indicate that SCZ is associated with a network-wide reduction of PFC pyramidal neuron activity that could lead to reduced excitatory drive of cINs (Berman et al., 1992; Buchsbaum et al., 1984a,b). This could result in downregulation of various activity-dependent cIN

parameters, such as PV or GAD expression. Coupled with evidence for loss of dendritic spines (Garey et al., 1998; Glantz and Lewis, 2000), the above findings suggest that the onset of SCZ may originate from reduced excitatory neurotransmission in the PFC, resulting in secondary cIN deficits. Interestingly, adolescence is normally associated with extensive pruning of excitatory connectivity within the PFC (Mirmics et al., 2000). Since plasticity of excitatory connectivity during adolescence is influenced by the maturation and function of PV⁺ cINs (Katagiri et al., 2007), early cIN dysfunction could conceivably contribute to overpruning of excitatory connectivity onto pyramidal neurons early in the illness progression, which would then result in the reduction of cIN activity.

In addition to pyramidal neuron excitation, two other mechanisms associated with SCZ have also been suggested to influence cIN activity. PV⁺ cINs receive stimulatory dopaminergic inputs (Mrzljak et al., 1996) that increase during adolescence (Tang et al., 2011; Tseng and O'Donnell, 2007; Tseng et al., 2006). In a hippocampal rat lesion model of SCZ, PFC dysfunction involves alteration of cIN responsiveness to dopamine (DA) (Gruber et al., 2010). In a mouse model of SCZ in which striatal D2 receptor activity is genetically enhanced, resulting in decreased DA in the PFC, GABAergic inputs onto cortical pyramidal neurons are also decreased (Li et al., 2011). Therefore, reduced cortical DA can result in dampened interneuron activity, and is thus a potential upstream mediator of cIN-related pathology in SCZ.

Finally, cholinergic inputs provide a critical excitatory drive to cINs (Arnaiz-Cot et al., 2008; Mok and Kew, 2006) and appear to mainly target cINs during the first two weeks of postnatal development (Janiesch et al., 2011). Cholinergic terminals can also enhance GABA release at perisomatic synapses onto hippocampal pyramidal neurons (Tang et al., 2011). In addition, cholinergic antagonists block PV⁺ cIN-mediated gamma oscillations in the hippocampus, while nicotine administration reduces the methylation status of the GAD67 promoter (Satta et al., 2008). Post-mortem findings on cholinergic deficits are sparse, but some evidence exists for a reduction in SCZ brains (Freedman et al., 2000; Guan et al., 1999; Holt et al., 1999; Hyde and Crook, 2001).

In sum, due to extensive connectivity and crosstalk between different neurotransmitter systems in the cortex, a deficit in any of these systems could induce significant changes within the circuitry. Thus, whether the neuropathology of SCZ originates in excitatory pyramidal neuron connectivity, inhibitory cINs, or subcortical DA or cholinergic systems remains unclear. Regardless of the molecular and genetic causes of SCZ, cIN dysfunction is a consistent symptom and remains a promising therapeutic target.

Future directions

Research over the last decade has significantly advanced our understanding of cIN function. While cINs appear to play a vital role in the etiology of SCZ, there are still many questions that remain unanswered. A significant challenge in studying the genetic basis of SCZ is generating accurate models of the disorder. Single gene knockouts may replicate certain phenotypes associated with SCZ and provide potential tools to understand the molecular and genetic mechanisms underlying these phenotypes. However, transgenic models that better mimic the genetic mutations in humans, such as Lgd1/Df(16^{+/-}) mice, are promising tools to study disease mechanisms in which cIN phenotypes can further be deciphered.

The advent of embryonic stem cell (ESC) and induced pluripotent stem cell (iPSC) technology has opened up a new gateway for studying normal neuronal development and disease (Cundiff and Anderson, 2011; Petros et al., 2011). Recently, several groups have succeeded in generating cINs from mouse (Danjo et al., 2011; Maroof et al., 2010) and human (Goulburn et al., 2011) ESCs. The ability to produce an unlimited source of cINs will expand our ability to study hypotheses on interneuron dysfunction in SCZ. In addition, the ability to create patient specific iPSCs permits the study of different genetic predispositions

to SCZ. Several groups have successfully created iPSCs from SCZ patients (Brennand et al., 2011; Chiang et al., 2011; Pedrosa et al., 2011), with some evidence that iPSC-derived neurons from SCZ patients have general defects in neuronal connectivity (Brennand et al., 2011). Application of this technology to the study of specific hypotheses on cortical pyramidal and interneuron dysfunction in SCZ promises to open new avenues of research on the cellular and molecular bases, and treatments, of this highly debilitating and treatment-resistant mental illness.

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