Complexin Controls Spontaneous and Evoked Neurotransmitter Release by Regulating the Timing and Properties of Synaptotagmin Activity

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| As Published | http://dx.doi.org/10.1523/jneurosci.3212-12.2012 |
| Publisher | Society for Neuroscience |
| Version | Final published version |
| Accessed | Sat Nov 05 02:47:30 EDT 2016 |
| Citable Link | http://hdl.handle.net/1721.1/79719 |
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Neurotransmitter release following synaptic vesicle (SV) fusion is the fundamental mechanism for neuronal communication. Synaptic exocytosis is a specialized form of intercellular communication that shares a common SNARE-mediated fusion mechanism with other membrane trafficking pathways. The regulation of synaptic vesicle fusion kinetics and short-term plasticity is critical for rapid encoding and transmission of signals across synapses. Several families of SNARE-binding proteins have evolved to regulate synaptic exocytosis, including Synaptotagmin (SYT) and Complexin (CPX). Here, we demonstrate that Drosophila CPX controls evoked fusion occurring via the synchronous and asynchronous pathways. cpx<sup>−/−</sup> mutants show increased asynchronous release, while CPX overexpression largely eliminates the asynchronous component of fusion. We also find that SYT and CPX coregulate the kinetics and Ca<sup>2+</sup> co-operativity of neurotransmitter release. CPX functions as a positive regulator of release in part by coupling the Ca<sup>2+</sup> sensor SYT to the fusion machinery and synchronizing its activity to speed fusion. In contrast, synt<sup>−/−</sup>; cpx<sup>−/−</sup> double mutants completely abolish the enhanced spontaneous release observe in cpx<sup>−/−</sup> mutants alone, indicating CPX acts as a fusion clamp to block premature exocytosis in part by preventing inappropriate activation of the SNARE machinery by SYT. CPX levels also control the size of synaptic vesicle pools, including the immediate releasable pool and the ready releasable pool—key elements of short-term plasticity that define the ability of synapses to sustain responses during burst firing. These observations indicate CPX regulates both spontaneous and evoked fusion by modulating the timing and properties of SYT activation during the synaptic vesicle cycle.

Introduction

Synaptic vesicles (SV) can fuse either spontaneously, or wait in a primed and fusion–competent state for evoked Ca<sup>2+</sup> influx to trigger activation of the SNARE complex fusion machinery (Sollner et al., 1993; Chen et al., 1999; Vrijic et al., 2010). The SNARE proteins synaptobrevin/VAMP, syntaxin, and SNAP-25 assemble into an α-helical coiled-coil structure that brings the SV and plasma membrane in close proximity for fusion (Sutton et al., 1998). During evoked release, vesicles can fuse immediately through a synchronous pathway, or with a small delay via an asynchronous release mechanism. The synaptic vesicle protein synaptotagmin 1 (SYT) functions as the synchronous Ca<sup>2+</sup> sensor and engages lipids and SNAREs following Ca<sup>2+</sup> influx (Geppert et al., 1994; Yoshihara and Littleton, 2002; Choi et al., 2010; Kochubej and Schneggenburger, 2011). The SNARE binding protein complexin (CPX) also regulates both evoked fusion and spontaneous release (minis) (Reim et al., 2001; Giraudo et al., 2006; Huntwork and Littleton, 2007; Maximov et al., 2009; Yang et al., 2010; Hobson et al., 2011; Martin et al., 2011). Although CPX and SYT are key regulators of neurotransmitter release, the mechanisms by which SYT and CPX act to orchestrate fusion are still unclear. SYT contains an N-terminal synaptic vesicle transmembrane anchor and a cytoplasmic region containing two Ca<sup>2+</sup>-binding C2 domains (Perin et al., 1990). Studies of SYT in Drosophila indicate Ca<sup>2+</sup> binding to the C2B domain triggers synchronous fusion (Mackler et al., 2002; Yoshihara et al., 2010), while Ca<sup>2+</sup> binding to the C2A domain is required to suppress asynchronous release (Yoshihara et al., 2010) and help facilitate synchronous fusion (Striegel et al., 2012). In contrast to the Ca<sup>2+</sup>-binding activity of SYT, CPX lacks Ca<sup>2+</sup>-binding sites and is a small cytoplasmic protein with a central α-helix that interacts with the SNARE complex (McMahon et al., 1995; Pabst et al., 2000; Bracher et al., 2002). SNARE binding by CPX functions to facilitate synaptic vesicle release (Reim et al., 2001; Xue et al., 2009; Cho et al., 2010; Xue et al., 2010) and allows CPX to act as a fusion clamp to prevent premature exocytosis in the absence of Ca<sup>2+</sup> (Huntwork and Littleton, 2007; Maximov et al., 2009). How CPX and SYT coordinate whether SV fusion occurs spon-

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Neurotransmitter Release by Regulating the Timing and Properties of Synaptotagmin Activity


This work was supported by NIH Grant NS40296 to J.T.L. We thank Yun Song for help with Drosophila genetics and Robin Stevens for the synaptogyrin antisera. R.A.J. was a recipient of the PEW Latin American Fellows Program in the Biomedical Sciences.

The authors declare no competing financial interests.

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Results

CPX regulates spontaneous and evoked fusion rates

Our previous studies revealed that cpx null mutants (cpx<sup>−/−</sup>) show a dramatic elevation in spontaneous fusion at Drosophila NMJs (Huntwork and Littleton, 2007). To further examine how CPX regulates release, we characterized spontaneous release parameters in cpx<sup>−/−</sup>, cpx<sup>+/−</sup>, and CPX overexpression lines that scale the levels of CPX from 0 to ~250% of control as shown by Western analysis (Fig. 1A). Manipulations of CPX levels did not alter basic synaptic substructure visualized by immunocytochemistry, as active zone apposition to glutamate receptor fields and glutamate receptor cluster size was similar to controls (data not shown). As shown in Figure 1B, spontaneous fusion events from single SVs are easily distinguished from basal noise in the absence of stimulation. cpx<sup>−/−</sup> null mutants displayed a ~40-fold increase in spontaneous frequency (80.6 ± 9.3 Hz) compared with controls (2.6 ± 0.2 Hz) at muscle 6 NMJs. The dramatic increase in spontaneous release was not reduced in 0 mM extracellular Ca<sup>2+</sup> (Huntwork and Littleton, 2007) or in the presence of Cd<sup>2+</sup>, which blocks presynaptic Ca<sup>2+</sup> entry (Fig. 1D), indicating increased spontaneous release in cpx<sup>−/−</sup> does not require extracellular Ca<sup>2+</sup> influx. Heterozygous cpx<sup>+/−</sup> animals with a 50% reduction in CPX protein levels (Fig. 1A) also displayed an elevated spontaneous release frequency of 7.3 ± 0.6 Hz (Fig. 1B, D). Overexpression of CPX presynaptically by ~2.4-fold using the UAS-GAL4 system (Fig. 1A) reduced baseline spontaneous release to 1.5 ± 0.1 Hz (Fig. 1B, D), indicating CPX is rate-limiting as a fusion clamp at Drosophila NMJs. The increase in spontaneous release observed at cpx<sup>−/−</sup> muscle 6 NMJs made it difficult to analyze single unitary fusion events. To bypass summation effects at muscle 6, we examined neighboring muscle 5 NMJs, a synapse with ~4-fold fewer release sites. Similar to muscle 6, cpx<sup>−/−</sup> increased spontaneous release ~40-fold (16 ± 2 Hz in cpx<sup>−/−</sup> compared with 0.5 ± 0.1 Hz in controls, Fig. 1C,D). The reduced frequency at muscle 5 allowed a detailed quantal analysis of isolated single SV fusion events. Quantal size and individual vesicle release kinetics, including the rise and decay times, were not altered in cpx<sup>−/−</sup> (Fig. 1E,F), indicating CPX does not modulate SV fusion pore dynamics for quantal glutamate discharge, but rather controls the overall rate of spontaneous fusion events.

In addition to its role as a fusion clamp, CPX is required for normal levels of evoked release (Reim et al., 2001; Huntwork and Littleton, 2007). To determine if CPX is rate-limiting in its role as a positive regulator of release, we assayed evoked properties in cpx<sup>−/−</sup>, cpx<sup>+/−</sup>, and CPX overexpression lines. We observed that cpx<sup>−/−</sup> has a ~60% reduction in evoked release amplitude, while overexpression of CPX enhanced evoked responses by ~25% (Fig. 2A). Expressing a transgenic UAS-cpx in the cpx<sup>−/−</sup> background with the neuronal drive elav-GAL4 fully rescued release defects in the mutant (Fig. 2A), suggesting CPX functions solely in the presynaptic compartment in Drosophila to control neurotransmitter release. Heterozygous cpx<sup>+/−</sup> lines reduced release by ~15% (214 ± 20 nA in cpx<sup>−/−</sup> compared with 260 ± 20 nA in controls, data not shown), indicating CPX is rate-limiting for both spontaneous and evoked release. To examine whether the effect of CPX on evoked release was mediated by shifting Ca<sup>2+</sup> affinity versus altering Ca<sup>2+</sup> co-operativity, we measured the Ca<sup>2+</sup> dependence of fusion in cpx<sup>−/−</sup> and CPX overexpression lines (Fig. 2B). Surprisingly, manipulations of CPX levels altered Ca<sup>2+</sup> co-operativity, with a reduction in the Ca<sup>2+</sup> dependence of release from 3.3 in controls to 2.1 in cpx<sup>−/−</sup> mutants, similar to
Co-operativity changes found in syt\(^{-/-}\) mutants (Littleton et al., 1994; Yoshihara and Littleton, 2002). In contrast, CPX overexpression enhanced Ca\(^{2+}\) co-operativity from 3.3 to 3.9. These data indicate the Ca\(^{2+}\) dependence of release critically depends on CPX levels, suggesting a potential interplay between CPX and the Ca\(^{2+}\) sensor SYT in triggering evoked release.

**CPX enhances the speed of evoked quantal release**

The EPSC recorded in the muscle after evoking an action potential represents the macroscopic summation of multiple individual miniature EPSCs (mEPSCs) that occur across many release sites. After nerve stimulation, quantal release is activated with a certain probability during the time window of elevated intratermal Ca\(^{2+}\). Evoked SV fusion occurs through a rapid SYT-regulated synchronous fusion pathway and a slower SYT-independent asynchronous pathway (Geppert et al., 1994; Yoshihara and Littleton, 2002; Xu et al., 2012). To determine whether CPX differentially regulates these distinct pathways, we examined synchronous and asynchronous release in cpx\(^{-/-}\) mutants and CPX overexpression lines (Fig. 2C–G). Comparing the quantal release rate normalized to the maximum response (Fig. 2C), evoked vesicle release was slowed in cpx\(^{-/-}\) mutants (mean time constant = 12.9 ± 1.2 ms) and enhanced by CPX overexpression (mean time constant = 10.6 ± 1.5 ms) compared with controls (mean time constant = 11.9 ± 1.3 ms). In addition, cpx\(^{-/-}\) mutants reduced the amount of synchronous release, while increasing the asynchronous component of vesicle fusion (Fig. 2E,F). In contrast, CPX overexpression almost completely suppressed all asynchronous fusion (Fig. 2E,F). The average asynchronous component in controls was 5.0 ± 1.5%, compared with 15 ± 2.9% in cpx\(^{-/-}\) and 0.7 ± 0.4% in CPX overexpression animals. The time constant for the kinetics of the slow component of release was not affected by CPX levels (Fig. 2G), indicating CPX controls the relative amount of fusion occurring via the synchronous or asynchronous pathway. Part of the slower kinetics of release observed in the evoked responses in cpx\(^{-/-}\) mutants could in theory be associated with abnormal postsynaptic responses due to the high amount of spontaneous neurotransmitter release. To observe whether there is more miniature fluctuation during the evoked responses in cpx\(^{-/-}\), we recorded evoked responses at the muscle 5. Control synapses showed a synchronous evoked response with lower amplitude than muscle 6, in agreement with fewer release sites at this muscle. However, cpx\(^{-/-}\) synapses not only show a reduction in the evoked amplitude compared with controls, but also an increase in the number of miniature fluctuations during a 50 ms window following release. The mean number of distinguishable events in control (1.05 ± 0.01) is far less than that observed in cpx\(^{-/-}\) (9.1 ± 0.5; Student’s t test, \(p < 0.001\)). The instantaneous frequency of events evoked in cpx\(^{-/-}\) (182 ± 10 Hz) surpasses tenfold the rate of spontaneous events observed at rest in the same synapses
Dashed lines represent the best fit for the slow component of release evaluated during the final 30 ms of the response. Mean time constants in the genotypes were not significantly different and are as follows: control, 11.9 ms; cpx−/−, 10.0 ± 1.2 ms; rescue, 274 ± 30 nA; OE-CPX, 320 ± 30 nA. Student’s t test revealed significant differences between control and cpx−/− (p < 0.01), rescue and cpx−/− (p < 0.01), and control and OE-CPX (p < 0.01). The average EPSC normalized to the maximal amplitude in each genotype is presented with a magnified time scale on the right. Right, Representative EPSCs recorded at muscle 5 in the presence of 2 mM external Ca2+ and asynchronous (dash line) and synchronous (solid line) release. Mean amplitudes in the genotypes are as follows: control, 34 ± 4 nA; cpx−/−, 12 ± 2 nA. Student’s t test revealed significant differences between control and cpx−/− (p < 0.001) and control and OE-CPX (p < 0.03). C, Average normalized responses plotted on a semi logarithmic graph to display their components. Dashed lines represent the best fit for the slow component of release evaluated during the final 30 ms of the response. Mean time constants in the genotypes were not significantly different and are as follows: control, 11.9 ± 1.3 ms; cpx−/−, 12.9 ± 1.2 ms; OE-CPX, 10.6 ± 1.5 ms. D, Cumulative release normalized for the maximum in 2.0 mM Ca2+ for each genotype. Each trace was adjusted to a double exponential fit. Mean charge transferred in the genotypes are as follows: control, 1.53 ± 0.11 nC; cpx−/−, 2.1 ± 0.1 nC; OE-CPX, 3.9 ± 0.2 nC. Student’s t test revealed significant differences between control and cpx−/− (p < 0.001) and control and OE-CPX (p < 0.01). E, The fast and slow components of release are plotted to show synchronous (solid line) and asynchronous (dash line) release. F, Quantification of the synchronous and asynchronous components of release for each genotype. The average asynchronous component in each genotype is as follows: control, 5.1 ± 1.5%; cpx−/−, 15 ± 2.9%; OE-CPX, 0.7 ± 0.4%. Student’s t test revealed significant differences between control and cpx−/− (p < 0.01) and control and OE-CPX (p < 0.01). G, Quantification of the time constants for synchronous and asynchronous release kinetics in each genotype is plotted. Student’s t test revealed no significant differences between the genotypes. The data represent recordings of mean responses in at least five different animals for each genotype for all panels. Error bars, SEM.

(Fig. 1C,D). Comparative analyses of the average evoked responses between control and cpx−/− produce the same behavior at muscle 6. These results indicate that the slower kinetic responses observed in cpx−/− synapses are a consequence of an increase in delayed fusion events, not due to postsynaptic defects. In summary, the absence of CPX resulted in increased asynchronous release, while CPX overexpression largely eliminated the asynchronous component of fusion.

To further analyze the ability of CPX to regulate transmission speed, we examined how changes in Ca2+ concentration altered CPX-induced phenotypes. The speed of evoked release increases with elevated Ca2+ levels (Katz and Miledi, 1968; Felmy et al., 2003). A change in the rising face of the EPSC is indicative that the quantal release process is activated with a different probability. We compared evoked release kinetics in low (0.2 mM) versus high (2.0 mM) extracellular Ca2+ (Fig. 3). In control animals, the ini-
tial speed of synchronous release measured by the rise time of the evoked current was increased ~2-fold in elevated Ca^{2+} (Fig. 3A, B). Overexpression of CPX resulted in a similar twofold faster rise-time in low Ca^{2+} compared with controls, suggesting CPX overexpression speeds quantal SV fusion similar to the effects observed after Ca^{2+} elevation. In high Ca^{2+}, there is no change in rise time induced by CPX overexpression, indicating release speed is saturated in these conditions. In contrast, cpx^{-/-} mutants exhibit slower quantal release in both high and low Ca^{2+}, indicating CPX is a critical regulator of transmission speed. Analysis of the mean rise time for evoked responses at 0.2 mM Ca^{2+} demonstrated that cpx^{-/-} mutants slowed the initial rise phase to ~4.5 ± 0.4 ms, while CPX overexpression increased the rise time to ~1.2 ± 0.1 ms compared with controls (2.7 ± 0.3 ms). We also observed that the levels of CPX regulated overall quantal release rates, in addition to the initial speed of fusion, as measured by the total rate of release (Fig. 3C, D). The mean quantal release rates in 0.2 mM Ca^{2+} measured when 90% of the total charge was transferred were 21.3 ± 2.1 ms in control, 37.2 ± 3.7 ms in cpx^{-/-}, and 15.5 ± 1.6 ms in animals overexpressing CPX. Increased CPX levels enhanced the overall quantal release rate similar to the effects of elevating external Ca^{2+} (Fig. 3D).

Use-dependent synaptic plasticity regulated by CPX

Synaptic vesicle recycling and the maintenance of specific SV pools are critical for neuronal communication during high-frequency tetanic stimulation. Three major functional pools of synaptic vesicles—the immediate releasable pool (IRP), the ready releasable pool (RRP), and the reserve pool (RP)—have been described at multiple synapses, including the Drosophila NMJ (Rizzoli and Betz, 2005). Vesicles from the IRP contribute to phasic neuronal responses and have been associated morphologically with docked synaptic vesicles (Elmqvist and Quastel, 1965; Schneggenburger et al., 1999; Delgado et al., 2000). Vesicles from the RRP drive tonic neuronal responses and are mobilized during stimulation to prevent vesicle depletion at active zones. Synaptic vesicle recycling is largely responsible for sustaining release after RRP mobilization, with a minor contribution from the RP (Heuser and Reese, 1973; Delgado et al., 2000; Zucker and Regehr, 2002). To examine how CPX regulates short-term plasticity and synaptic vesicle pools during high-frequency tetanic stimulation, we examined use-dependent changes in evoked release in 2 mM external Ca^{2+} during a 10 Hz stimulation. The initial evoked responses undergo a rapid and transient depression as vesicle pools become depleted within the first 10–15 stimuli (Fig. 4A–C). The initial fast component of depression is described by a single exponential that rapidly reaches a constant value. We attribute this early phase of synaptic depression to depletion of the IRP, with recovery through recruitment of vesicles from the RRP. The number of vesicles in the IRP can be estimated by integrating release during the depression and subtracting the constant RRP contribution. The average IRP in controls is 200 ± 19 vesicles (Fig. 4A–D). We previously quantified active zone number at Drosophila muscle 6 in our control line (Huntwork and Litteleton, 2007). Muscle 6 contains ~500 active zone release sites, suggesting the IRP represents ~0.4 vesicles/active zone at resting synapses (similar to what we measured for membrane docked vesicles per active zone; see Fig. 6C,F). The IRP is reduced in cpx^{-/-} to 78 ± 8 vesicles (Fig. 4G,D). In contrast, CPX overexpression enhances the IRP pool size to 284 ± 28 vesicles (Fig. 4C,D). The second component of depression occurs after the initial rapid reduction in release and continues for up to the ~1000th stimuli before reaching steady-state levels (see control in Fig. 4E). This phase of depression represents delivery of vesicles from the RRP, and can be calculated by measuring the integral of the decaying evoked response minus the steady-state sustained component of release that is eventually reached and associated with SV recycling dynamics (Delgado et al., 2000). CPX levels had a strong impact on the RRP (Fig. 4G,H). The RRP pool size in control was 31,600 ± 3000 vesicles, while cpx^{-/-} had an RRP of 17,400 ± 1800 vesicles (Fig. 4G,H). Animals overexpressing CPX displayed an increased RRP size of 56,700 ± 5500 vesicles (Fig. 4G,H). By comparing the sustained response after the 1000th stimuli to continued 10 Hz stimulation in mutant and overexpression lines, we found no change in the size of the overall

Figure 3. CPX and Ca^{2+} increase the speed of evoked quantal release rate. A, Average traces of EPSCs normalized to the maximal amplitude in control (black), cpx^{-/-} (red), and CPX overexpression (OE-CPX, blue) synapses in 0.2 and 2.0 mM external Ca^{2+}. B, Quantification of average rise time in each genotype. Mean rise times at 0.2 mM Ca^{2+} are as follows: control, 2.7 ± 0.3 ms; cpx^{-/-}, 4.5 ± 0.4 ms; OE-CPX, 1.2 ± 0.1 ms. Student’s t test revealed significant differences between control and OE-CPX (p < 0.01), control and cpx^{-/-} (p < 0.01), control at 0.2 and 2 mM (p < 0.01), and cpx^{-/-} at 0.2 and 2 mM (p < 0.01). Mean rise times at 2 mM Ca^{2+} are as follows: control, 1.1 ± 0.1 ms; cpx^{-/-}, 1.8 ± 0.2 ms; OE-CPX, 1.1 ± 0.1 ms. Student’s t test revealed significant differences between control and cpx^{-/-} (p < 0.01), control and OE-CPX synapses at two external Ca^{2+} concentrations. Dash lines indicate the time at which 90% of the total release has occurred during a single stimulus. D, Quantification of release time when 90% of the total charge was transferred in each condition. Mean release time in the strains at 0.2 mM Ca^{2+} are as follows: control, 21.3 ± 1.1 ms; cpx^{-/-}, 37.2 ± 3.72 ms; OE-CPX, 15.5 ± 1.6 ms. Student’s t test revealed significant differences between control and cpx^{-/-} (p < 0.01), control and OE-CPX (p < 0.01), control at 0.2 and 2 mM (p < 0.01), control and cpx^{-/-} at 0.2 and 2 mM (p < 0.01), and OE-CPX at 0.2 and 2 mM (p < 0.01). Mean release time at 2 mM Ca^{2+} are as follows: control, 8.3 ± 0.9 ms; cpx^{-/-}, 18.1 ± 1.8 ms; OE-CPX, 6.7 ± 0.7 ms. Student’s t test revealed significant differences between control and OE-CPX (p < 0.01) and control and cpx^{-/-} (p < 0.01). The data in all panels represent recordings of mean responses in at least five different animals for each genotype. Error bars, SEM.
recycling rate (Fig. 4E). The average quantal content during steady-state release is 106 ± 10 quanta/stimulus in controls, compared with 98 ± 9 quanta/stimulus in cpx⁻/⁻ and 110 ± 12 quanta/stimulus in overexpression lines.

To further analyze use-dependent synaptic properties modulated by CPX, release during high-frequency stimulation in lower Ca²⁺ (0.2 mM) was assayed. Control synapses rapidly facilitate in low Ca²⁺, followed by a slower augmentation of the response (Fig. 5F). The increased release in low Ca²⁺ is hypothesized to be due to enhanced fusion from the IRP and potentiation of RRP exocytosis during the stimulus train. As shown in Figure 5A–D, cpx⁻/⁻ synapses failed to show a rapid facilitation, while CPX overexpression resulted in faster and more robust facilitation than control synapses. Similarly, when we assayed EPSC responses during the later period of tetanic stimulation in low Ca²⁺, we observed that while control synapses potentiated their response twofold by the 500th stimuli, cpx⁻/⁻ mutants showed a reduced augmentation of only 1.3-fold (Fig. 5F–I). CPX overexpression increased EPSC amplitude threefold by the 500th stimuli, resulting in an enhanced augmentation. Quantification of the total vesicle number released during the stimulation protocol is shown in Figure 5J. Together, these findings indicate CPX not only regulates evoked release kinetics, but also controls the size of the IRP and RRP—key elements that define the ability of synapses to sustain responses during burst firing.

One mechanism by which CPX might control the size of the releasable vesicle pool is through its ability to regulate spontaneous release rates. The dramatic enhancement in spontaneous fusion in cpx⁻/⁻ could partially deplete vesicles within the IRP and RRP pools, leading to alterations in vesicle dynamics during tetanic stimulation. To determine whether this model would be predictive for the depletion in vesicle pools we observe, we first analyzed how increased spontaneous release would deplete vesicle number. cpx⁻/⁻ mutant synapses show a stable resting potential baseline despite the elevated mini frequency (Fig. 6A). This allowed us to determine the cumulative spontaneous release by integrating charge transferred during rest at cpx⁻/⁻ synapses (Fig. 6B). Using this method of quantification, cpx⁻/⁻ mutants release between 150 and 200 vesicles per second through spontaneous fusion (Fig. 6C). A similar rate of vesicle fusion can be triggered at control synapses by stimulating at 0.5 Hz in 2 mM Ca²⁺ (Fig. 6D). This stimulation causes a steady-state release of ~200 vesicles per stimulus by the 20th pulse (Fig. 6E), similar to the rate of quanta released at rest in cpx⁻/⁻. Delivering a 10 Hz pulse to control synapses prestimulated at 0.5 Hz results in a severe reduction in the initial fast component of depression that corresponds to IRP pool depletion (Fig. 6D–F), similar to what we observe in cpx⁻/⁻. These results are consistent with a loss of releasable vesicles through enhanced spontaneous release in cpx⁻/⁻ mutants. To determine whether the defect in vesicle release during high-frequency stimulation in cpx⁻/⁻ mutants represents functional modulation of the release machinary or defects in SV docking or SV number, we examined the ultrastructure of cpx⁻/⁻ synapses by electron microscopy. No change in SV number at or around active zones before or after nerve stimulation was observed (Fig. 6G,H). These results indicate CPX likely me-
CPX regulates short-term synaptic potentiation. A, Representative EPSCs in low external calcium (0.2 mM) in control (black), cpx<sup>-/-</sup> (red), and CPX overexpression (blue) synapses during a short 10 Hz tetanic stimulation. B, The average response to the first 10 stimuli normalized to the first response during the tetanus is shown for control (black), cpx<sup>-/-</sup> (red), and CPX overexpression (blue) synapses. The average fast tetanic facilitation in each genotype is as follows: control, 1.6 ± 0.1; cpx<sup>-/-</sup>, 1.1 ± 0.1; OE-CPX, 2.4 ± 0.2. Student’s t test revealed significant differences between control and cpx<sup>-/-</sup> (<p < 0.01) and control and OE-CPX (<p < 0.001). The average paired-pulse facilitation at 10 Hz in independent measurements for the genotypes are as follows: control, 1.3 ± 0.3; cpx<sup>-/-</sup>, 1.1 ± 0.1; OE-CPX, 1.4 ± 0.1. Student’s t test revealed significant differences between control and cpx<sup>-/-</sup> (<p < 0.01) and control and OE-CPX (<p < 0.01). C, Average cumulative quantal content during the first 50 responses to a 10 Hz stimulation in each genotype. D, Average cumulative quantal release is graphed for each genotype. E, Quantification of the fast releasable pool in each genotype is shown. Average values in quanta are as follows: control, 265 ± 15; cpx<sup>-/-</sup>, 202 ± 12; OE-CPX, 335 ± 18. Student’s t test revealed significant differences between control and cpx<sup>-/-</sup> (<p < 0.01) and control and OE-CPX (<p < 0.01). F, Representative EPSCs in control, cpx<sup>-/-</sup>, and CPX overexpression synapses during a long tetanic stimulation of the nerve shows the slower augmentation phase of facilitation. G, The average 500 responses normalized to the first response during the tetanus in control (black), cpx<sup>-/-</sup> (red), and CPX overexpression (blue) synapses is shown. Average potentiation (reached at the 500th stimuli) in the genotypes are as follows: control, 2.0 ± 0.2; cpx<sup>-/-</sup>, 1.3 ± 0.1; OE-CPX, 3.0 ± 0.2. Student’s t test revealed significant differences between control and cpx<sup>-/-</sup> (<p < 0.01) and control and OE-CPX (<p < 0.01). H, Average cumulative quantal content in a long tetanus in each genotype. Average quantal content at the end of the stimulation in the genotypes are as follows: control, 25.6 ± 1.5 quanta; cpx<sup>-/-</sup>, 15.9 ± 16.7 quanta; OE-CPX, 37.4 ± 2.0 quanta. Student’s t test revealed significant differences between control and cpx<sup>-/-</sup> (<p < 0.01) and control and OE-CPX (<p < 0.01). I, Average cumulative quantal release is graphed in each genotype during the augmentation phase for each genotype to estimate the slow releasable pool. J, Quantification of the slow releasable pool in each genotype. Average values in kilo quanta are as follows: control, 8.6 ± 0.9; cpx<sup>-/-</sup>, 6.6 ± 0.7; OE-CPX, 12.2 ± 1.2. Student’s t test revealed significant differences between control and cpx<sup>-/-</sup> (<p < 0.01) and control and OE-CPX (<p < 0.01). All recordings were performed at 0.2 mM external Ca<sup>2+</sup>. The frequency of the tetanic stimulation was fixed at 10 Hz. The data in all panels represent recordings of mean responses in at least six different animals for each genotype. Error bars, SEM.

CPX regulates SYT function during evoked and spontaneous synaptic vesicle fusion

The mechanisms that underlie the ability of CPX to clamp spontaneous release and facilitate evoked fusion are unclear. One model is that CPX directly binds the SNARE complex and clamps fusion by preventing full SNARE zippering (Giraudo et al., 2009) or generating a “zigzag” SNARE array incompatible with fusion (Kümml et al., 2011). Consistent with a direct effect on SNARE complexes, mutations in CPX that block SNARE binding fail to rescue the increased frequency of spontaneous release (Choi et al., 2010). An additional mode of regulation suggested by our findings that CPX regulates the synchronicity and Ca<sup>2+</sup>-dependent fusion, we assayed evoked release properties in double mutant animals. Quantal content is reduced over a range of Ca<sup>2+</sup> concentrations in both mutants, with a shift in co-operativity to the right in both syt<sup>-/-</sup> and syt<sup>-/-</sup>; cpx<sup>-/-</sup> (Fig. 7C). In the absence of SYT alone, residual

diabetes molecular interactions required for generating fusion-ready synaptic vesicles (priming) that form the IRP and RRP, but does not uncouple processes required for morphological docking of vesicles at active zones.

During our high-frequency stimulation experiments, we detected an additional defect in the timing of fusion that appeared in cpx<sup>-/-</sup> mutants over the course of a stimulation train. Cpx<sup>-/-</sup> animals showed a progressive delay in the onset of the evoked response during a 10 Hz stimulation protocol. To characterize this defect, we quantified the initial rising phase of evoked responses during the first 20 stimulation events compared with the final 30 events during a 150 s 10 Hz tetanic stimulation train (Fig. 6I). At control synapses, we observed a small increase in the synaptic delay of ~0.2 ms when comparing the initial and final set of event delay intervals. In contrast, cpx<sup>-/-</sup> showed a dramatic increase in synaptic delay over the course of the stimulation, increasing to ~1 ms by the end of the train (Fig. 6I). These results indicate that loss of CPX increases synaptic delay during a stimulation train, consistent with CPX normally maintaining the rate of quantal release at control synapses.

The mechanisms that underlie the ability of CPX to clamp spontaneous release and facilitate evoked fusion are unclear. One model is that CPX directly binds the SNARE complex and clamps fusion by preventing full SNARE zippering (Giraudo et al., 2009) or generating a “zigzag” SNARE array incompatible with fusion (Kümml et al., 2011). Consistent with a direct effect on SNARE complexes, mutations in CPX that block SNARE binding fail to rescue the increased frequency of spontaneous release (Choi et al., 2010). An additional mode of regulation suggested by our findings that CPX regulates the synchronicity and Ca<sup>2+</sup>-dependent fusion, we assayed evoked release properties in double mutant animals. Quantal content is reduced over a range of Ca<sup>2+</sup> concentrations in both mutants, with a shift in co-operativity to the right in both syt<sup>-/-</sup> and syt<sup>-/-</sup>; cpx<sup>-/-</sup> (Fig. 7C). In the absence of SYT alone, residual
evoked SV fusion becomes asynchronous (Fig. 7D–I). Double mutants lacking both SYT and CPX reduce release more profoundly and show even slower asynchrony (Fig. 7D–I). Rise time and overall release rate are also slowed in syt<sup>−/−</sup>; cpx<sup>−/−</sup> compared with either mutant alone (Fig. 7G–I). Compared with mean rise time for evoked release in control animals of 1.0 ± 0.1 ms, syt<sup>−/−</sup>; cpx<sup>−/−</sup> double mutants had a rise time of 5.9 ± 0.6 ms. Single mutant analysis suggests SYT exerts a more prominent effect than CPX (mean rise time of 1.7 ± 0.2 ms in cpx<sup>−/−</sup> vs 2.6 ± 0.3 ms in syt<sup>−/−</sup>), but the loss of both proteins results in additive defects in total release and the speed of quantal release (Fig. 7C–I). Mean release time in control is 8.1 ± 0.8 ms compared with 18.5 ± 0.2 ms in cpx<sup>−/−</sup>, 38.9 ± 4.1 ms in syt<sup>−/−</sup>, and 57.8 ± 6.1 ms in syt<sup>−/−</sup>; cpx<sup>−/−</sup> double mutants. These results indicate that although SYT and CPX share similarities in their ability to control evoked fusion, each protein can also contribute independently to regulate release properties.

To further probe how SYT and CPX regulate release, we assayed the effects of overexpression of SYT alone versus overexpression of both proteins together at the synapse. Overexpression of SYT triggered an enhancement of release rate and the total amount of vesicles released (Fig. 8A). SYT overexpression also prolonged the rise time from 1.1 ± 0.1 ms in controls up to 3.8 ± 0.4 ms, indicating increased SYT levels lengthened the release window rather than simply enhancing synchronous fusion (Fig. 8B). We hypothesized that this effect might be mediated by a mismatch between SYT and CPX levels in regulating SNARE-dependent fusion. To test this model, we co-overexpressed both SYT and CPX together. Overexpression of both proteins reduced the rise time compared with SYT alone back to near control levels (1.1 ± 0.1 ms in controls compared with 1.8 ± 0.2 ms in strains overexpressing both proteins, Fig. 8B,C), indicating that increasing CPX levels can synchronize SYT function in triggering SV fusion.
**Discussion**

The regulation of SNARE activity is critical for controlling the speed and rate of synaptic vesicle fusion. Here we show that the SNARE-binding protein CPX can bidirectionally regulate spontaneous release, the speed of neurotransmission, Ca^{2+} cooperativity, and short-term synaptic plasticity. We find that the role of CPX as a fusion clamp to prevent spontaneous release results from regulation of the activity of the Ca^{2+} sensor SYT in vivo. CPX can also synchronize SYT activity during evoked release, suggesting a critical role for CPX as a regulator of SYT function during both spontaneous and evoked synaptic vesicle fusion. Beyond effects on spontaneous and evoked release, loss of CPX reduced the IRP and RRP pool of vesicles, similar to observations made in *C. elegans* cpx mutants (Hobson et al., 2011). We also observed that overexpression of CPX increased both the IRP and RRP synaptic vesicle pools. These effects of CPX on vesicle pools sizes resulted in changes in multiple aspects of synaptic plasticity, including alterations in depression, facilitation, and augmentation.

Alterations in the levels of either SYT or CPX modulate synaptic plasticity, including alterations in depression, facilitation, and augmentation.
taneous release rates by >40-fold, in contrast to the smaller increase in spontaneous release rate (~3-fold) observed in the absence of SYT. As such, CPX plays the major role as the synaptic vesicle fusion clamp at Drosophila synapses. Several models have been proposed to account for the ability of CPX to function as a fusion clamp. Prior studies in mammals suggested that the CPX N-terminal α-helical accessory domain that flanks the SNARE-binding region inhibits fusion by partially incorporating into the 4-helix bundle of the SNARE complex to prevent full zipping (Giraudo et al., 2009; Maximov et al., 2009). A second model suggests that CPX clamps release by cross-linking intermolecular SNARE complexes into a zig-zag array (Kümmel et al., 2011; Li et al., 2011). These in vitro assays suggest the clamping abilities of CPX may be independent of SYT. Although we previously found that SNARE binding is required for the clamping function of CPX in Drosophila (Choi et al., 2010), our in vivo analysis using syt<sup>−/−</sup>; cpx<sup>−/−</sup> double mutants demonstrate that the increased spontaneous release in cpx<sup>−/−</sup> requires SYT function. Our genetic studies support a model in which CPX-bound SNAREs interact with SYT in a distinct fashion compared with when CPX is absent. Recent FRET and crystallography analysis of the SYT-SNARE complex revealed that SNARE binding by SYT triggers a conformational state of the protein that mimics Ca<sup>2+</sup> binding (Choi et al., 2010; Vrlijc et al., 2010). In the absence of Ca<sup>2+</sup> or SNARE binding, SYT exists in an open state where the Ca<sup>2+</sup> binding loops in C2A and C2B are spread apart. Upon Ca<sup>2+</sup> or SNARE binding, the Ca<sup>2+</sup> binding loops are brought closer together, mimicking the spacing of the membrane penetrating loops of viral fusion proteins. A conformational change of SYT into a more fusogenic form triggered by SNARE interactions in the absence of CPX fits well with our in vivo observations on the mechanism of increased spontaneous fusion in cpx mutants.

Does coordination of SYT and CPX activity also control evoked release? We find that altering CPX levels up or down can shift the Ca<sup>2+</sup> co-operativity of release and the amount and speed of quantal vesicle release, similar to defects observed though manipulations of SYT activity (Littleton et al., 1994; Yoshihara and Littleton, 2002). In addition to the regulation of Ca<sup>2+</sup> co-operativity, we find that CPX functions to synchronize SYT activity in triggering fusion, as revealed by dual overexpression of the two proteins. Our findings match in vitro fusion assay systems where CPX facilitates the ability of SYT to drive Ca<sup>2+</sup>-dependent fusion of liposomes or cells containing surface-exposed SNAREs (Krishnakumar et al., 2011; Kyoung et al., 2011). Besides increasing Ca<sup>2+</sup> levels, CPX overexpression is one of the few known mechanisms to increase the speed of quantal synaptic vesicle fusion in vivo. We find that increasing CPX levels mimics the effects of increasing external Ca<sup>2+</sup> for evoked release—increasing both the amount and speed of quantal fusion.

The molecular mechanism by which CPX couples SYT to the fusion machinery to enhance the speed of nerve-triggered release is currently unclear. Prior work on synaptic transmission demonstrated that the time between action potential invasion and Ca<sup>2+</sup> entry through Ca<sup>2+</sup> channels is a major contributor to synaptic delay (Katz and Miledi, 1967). In addition to Ca<sup>2+</sup> channel opening, another source of delay occurs between Ca<sup>2+</sup> influx...
and activation of the fusion machinery (Chow et al., 1994; Sabatini and Regehr, 1996). We anticipate that CPX-SYT levels would regulate this key step, perhaps through an ability of CPX-bound SNARE complexes to serve as an efficient partner for a SYT-Ca\(^{2+}\) complex. Whether SYT and CPX can bind the SNARE complex at the same time is still unclear (Tang et al., 2006; Chicka and Chapman, 2009). Besides syt\(^{-/}\) and cpx\(^{-/}\) mutants, alterations in several other presynaptic proteins have been found to increase asynchronous during evoked release. In Drosophila, synapses lacking the active zone protein Bruchpilot show defects in coupling Ca\(^{2+}\) influx to vesicle fusion, although vesicle availability is not rate-limiting (Kittel et al., 2006). At mammalian Calyx of Held nerve terminals, the active zone protein RIM contributes to synaptic coupling by increasing Ca\(^{2+}\) channel density and synaptic vesicle docking (Han et al., 2011). A potential role for SYT and CPX in coupling Ca\(^{2+}\) channel function to fusion rate could also impact release kinetics, and we cannot rule out a key role for these proteins in this aspect of vesicle fusion. Similarly, although we did not observe any effects of CPX on the steady-state release rate, or find evidence of endocytotic defects by EM, we cannot rule out that CPX plays a more subtle role in regulating vesicle recycling as well.

Given our observations at the Drosophila NMJ, we propose a model to account for the effects of SYT and CPX activity on fusion. Generation of a fusion-ready vesicle would begin with the formation of SNARE complexes between a t-SNARE acceptor complex containing SNAP-25 and Syntaxin and the v-SNARE (synaptobrevin/VAMP). The SNARE proteins would zipper together via an energetically favorable coiled-coil interaction, bringing the lipid interface of the vesicle and plasma membrane into close proximity. After the initiation of SNARE complex assembly, several possible outcomes could then be triggered. At resting synapses, CPX would bind and stabilize the SNARE complex to generate fusion-ready primed vesicles that would enter the IRP. This CPX-clamped state would have to be overcome by a favorable SYT- Ca\(^{2+}\) interaction to initiate evoked fusion. Overexpression of CPX would enhance the probability of generating the clamped state, reducing spontaneous release and increasing vesicles residing in the fusion-ready IRP pool. Ca\(^{2+}\)-binding to SYT following an action potential would generate a more energetically favorable SYT-SNARE complex that fully zippers to trigger lipid perturbation and fusion. In the absence of CPX, the barrier to fusion normally achieved would be reduced, allowing SYT-SNARE interactions to more easily proceed to trigger enhanced spontaneous release even in the absence of Ca\(^{2+}\). One interesting observation from our data is that although CPX overexpression enhances the speed of fusion at lower Ca\(^{2+}\) (0.2 mM), it only increases the amount of evoked fusion at higher Ca\(^{2+}\) levels. If SYT and CPX compete for SNARE complex binding, the binding affinities are likely to be controlled by intracellular Ca\(^{2+}\) concentration in the case of SYT. CPX overexpression has similar effects on spontaneous release compared with evoked release in low Ca\(^{2+}\), suggesting a strong clamping function at low Ca\(^{2+}\). The energy necessary to liberate clamped vesicles is likely to be significantly higher following CPX overexpression. We hypothesize that as Ca\(^{2+}\) levels increase, enhanced SYT activity would surpass the energy required to unclamp more vesicles, and thus generate a larger number of vesicle fusion events.

Our results also shed light on the role of CPX and SYT in regulating whether fusion would proceed through a synchronous versus asynchronous pathway. Vesicles that have been clamped by CPX-SNARE interactions would be available for evoked synchronous release following Ca\(^{2+}\) entry. Asynchronous release, which normally represents a small component of overall fusion, would arise from SVs outside of the CPX-primed pool. Vesicles that bypass the CPX-primed state could also fuse spontaneously to generate the normally observed low mini release rate. In the absence of CPX, the probability of entering the primed state is reduced, resulting in higher rates of spontaneous release and a greater probability of asynchronous release during stimulation. In contrast, increased CPX levels would enhance the probability of vesicles entering the clamped state, resulting in decreased spontaneous release and the lack of asynchronous fusion observed following CPX overexpression. Given the numerous observations of altered CPX levels in many neurological and psychiatric diseases (Brose, 2008), an imbalance in the CPX/SYT ratio may functionally impact synaptic release properties in a host of brain diseases. Similarly, differential expression of SYT and CPX at synaptic subtypes within the brain may also contribute to the distinct release kinetics observed at different synapses.

References


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