Parallel processing of quickly and slowly mobilized reserve vesicles in hippocampal synapses

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Abstract Vesicles within presynaptic terminals are thought to be segregated into a variety of readily releasable and reserve pools. Trafficking between the pools is not well understood, but pools that are slow to *mobilize* when synapses are active are usually assumed to feed pools that are mobilized more quickly, in a series. However, results from electrophysiological studies of synaptic transmission suggested instead a parallel organization where vesicles within slowly and quickly mobilized reserve pools would separately feed independent reluctant- and fast-releasing subdivisions of the readily releasable pool, without intermixing. We now use FM-dyes to confirm the existence of multiple reserve pools at hippocampal synapses. We then confirm the new prediction that slowly and quickly mobilized reserve pools do not intermix, even when mobilized by high frequency stimulation. The result provides a simplifying new constraint on the dynamics of vesicle recycling within presynaptic terminals. The experiments additionally demonstrated extensive heterogeneity among synapses in the relative sizes of slowly and quickly mobilized reserve pools. The heterogeneity suggests equivalent heterogeneity in the probability of release among readily releasable vesicles that may be relevant for understanding information processing and storage.

Introduction

Chemical synapses exhibit striking dynamic changes in connection strength during repetitive use. The changes are termed *short-term plasticity* or *frequency dynamics*, and are thought to play an important role in how information is processed (***Tsodyks and Markram, 1997***; ***Abbott and Regehr, 2004***; ***Buonomano and Maass, 2009***). Multiple presynaptic vesicle trafficking mechanisms are involved, but the identity of the mechanisms, how they interact, and the implications for biological computation are not understood (***Neher, 2015***).

Most attempts at a detailed understanding begin with the premise that presynaptic vesicles are segregated into multiple *pools*, including at least one readily releasable pool and one reserve. Readily releasable vesicles are thought thought to be docked to *release sites* embedded within the active zone area of the plasma membrane of synaptic terminals, whereas reserves reside in the interior. Nevertheless, pools are typically not defined by morphological criteria but instead by the timing of *mobilization*, which is a general term for the full sequence of events required for constituent vesicles to undergo exocytosis. Based on this, the readily releasable pool has been divided into *fast-* and *slow-releasing* subdivisions at a wide variety of synapse types; slow-releasing readily releasable vesicles are often termed *reluctant* (***Wu and Borst, 1999***; ***Sakaba and Neher, 2001***; ***Moulder and Mennerick, 2005***). Reserves are less studied, but have likewise been divided

into quickly and slowly mobilized pools at some synapse types (***Neves and Lagnado, 1999***; ***Rizzoli and Betz, 2005***; ***Denker et al., 2011***).

A widespread premise has been that the pools are connected in a series where vesicles are transferred from slowly to quickly mobilized pools as diagrammed in ***Figure 1A*** (***Pieribone et al., 1995***; ***Hilfiker et al., 1999***; ***Denker and Rizzoli, 2010***; ***Rothman et al., 2016***; ***Miki et al., 2016***; ***Doussau et al., 2017***; ***Milovanovic et al., 2018***; ***Lin et al., 2022***). If so, reluctant vesicles would be docked to the same type of release site as fast-releasing vesicles, but in an immature priming state that could then transition to the mature, fast-releasing state. We refer to models with this premise as *homogeneous release site* models. However, a growing body of evidence suggests that reluctant vesicles are fully primed for release at a different kind of release site that is inherently inefficient at catalyzing exocytosis.

That is: Emerging optical imaging and molecular evidence indicates substantial heterogeneity among release sites, even within the same synapse (***Hu et al., 2013***; ***Müller et al., 2015***; ***Böhme et al., 2016***; ***Akbergenova et al., 2018***; ***Maschi and Klyachko, 2020***; ***Li et al., 2021***; ***Karlocai et al., 2021***; ***Gou et al., 2022***). And, to our knowledge, none of the homogeneous release site models that have been proposed so far can account for electrophysiological experiments where: the reluctant pool was only minimally depleted during moderately intense stimulation that exhausted the *fast-releasing* subdivision; and the reluctant vesicles could undergo exocytosis directly without entering the fast-releasing subdivision (***Mahfooz et al., 2016*** and ***Raja et al., 2019***, Figure5-figure supplement 1).

Because of this, our working model places fast-releasing and reluctant subdivisions of the readily releasable pool in parallel, which could be as in ***Figure 1B*** if based solely on the studies referenced so far. However, ***Figure 1C*** depicts a different possibility where quickly and slowly mobilized reserve pools are also arranged in parallel, and independently supply vesicles to corresponding fast-releasing and reluctant subdivisions of the readily releasable pool.

To our knowledge, no such fully parallel arrangement has been proposed explicitly, but it is implied by our own working model summarized in ***Figure 1D***. That is, a key element of our working model is that reserve vesicles are physically tethered in short chains to both reluctant and fast-releasing readily releasable vesicles (***Gabriel et al., 2011***; see ***Wesseling et al., 2019*** for supporting ultrastructural evidence). If correct, the reserves would have to wait in line for the readily releasable vesicle at the head of the chain to undergo exocytosis. As a consequence, reserve vesicles chained to reluctant readily releasable vesicles would appear to constitute a slowly mobilized reserve pool that would be processed in parallel with reserves chained to fast-releasing vesicles. Key for testing this idea: the difference compared to reserves attached to fast-releasing vesicles would only be large enough to measure when the frequency of stimulation is low enough that individual reluctantly releasable vesicles remain in the readily releasable pool for extended periods of time before undergoing exocytosis.

Here we begin by demonstrating that reserve vesicles at hippocampal synapses are segregated into multiple pools that can be distinguished by the timing of mobilization during low frequency stimulation. We then show further that the two types of reserves do not intermix, even when the frequency of stimulation is high, confirming that the two types are processed in parallel.

Results

We originally developed our working model to account for results from both primary cell culture and *ex vivo* slices (***Stevens and Wesseling, 1999b***; ***Garcia-Perez et al., 2008***; ***Gabriel et al., 2011***; ***Mahfooz et al., 2016***; ***Raja et al., 2019***). We chose to test the prediction that quickly and slowly mobilized reserve pools are processed in parallel in cell culture, because cultures are better suited for staining and destaining synaptic vesicles with FM-dyes, which could be used to distinguish between reserve pools.

In a first set of experiments, diagrammed atop ***Figure 2***, we began by staining vesicles within synapses with 60 s of 20 Hz electrical stimulation (1200 pulses) during extracellular bath application of FM4-64. We then removed the FM4-64 and washed with Advasep-7 or Captisol.

Advasep-7 and Captisol are related β-cyclodextrin derivatives that facilitate dye clearance from membranes when exposed to the extracellular space (***Kay et al., 1999***). The stain followed by wash procedure is thought to leave stained nearly all of the vesicles within synaptic terminals that can recycle, while eliminating most of the background fluorescence caused by binding to non-vesicular membrane (***Betz et al., 1992***; ***Ryan and Smith, 1995***; ***Chi et al., 2001***; ***Gaffield and Betz, 2006***). The vesicles then retain the dye until undergoing exocytosis, after which they likely destain completely as the dye is washed away into the extracellular space (***Figure 2–Figure Supplement 1***).

The idea was to use the time course of destaining to measure mobilization of stained vesicles. To asses the timing during low frequency stimulation, we monitored destaining in the continued presence of the β-cyclodextrin while stimulating at 1 Hz for 25 min (1500 pulses; blue in ***Figure 2A-B***). And finally, after a 4 min rest interval, we completed destaining to a low level with 100 s of 20 Hz stimulation (2000 pulses; red in ***Figure 2A-B***; see also ***Figure 2–Figure Supplement 2***).

Note that the concept of mobilization is not the same as pool depletion because mobilized stained vesicles are continuously replaced by unstained vesicles, either reconstituted from recycled vesicular membrane or recruited from other sources. Pool depletion during intense stimulation - particularly readily releasable pool depletion - was assessed in the electrophysiological studies that motivated the working model (reviewed in ***Wesseling, 2019***), but not directly in the present study.

Destaining time courses were only accepted for further analysis when baseline fluorescence loss was $\leq 1.5\,\%$/min. Baseline loss could have been caused by multiple factors including spontaneous exocytosis and focal drift of the microscope, but likely not by photobleaching (***Figure 2–Figure Supplement 3***).

The results were not compatible with straightforward models involving only a single pool containing vesicles that intermix quickly. That is, quickly mixing single pool models would predict that destaining at any point in time during 1 Hz stimulation would be a constant fraction of the amount of stain remaining within the pool at that time, meaning:

$$dF(t)/dt = -k \cdot F(t)$$

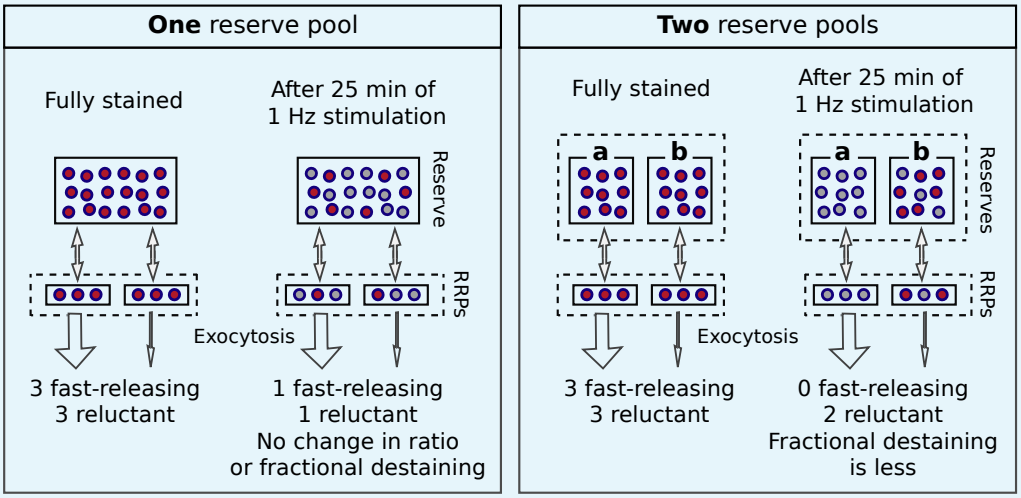
which is equivalent to:

$$k = \frac{-dF(t)/dt}{F(t)} \tag{1}$$

where k is a constant - equal to the fractional destaining (at any time) per unit of time - $F(t)$ is fluorescence intensity of the dye within the pool at time t, and $dF(t)/dt$ is the slope of the destaining time course at that time. However, the time course of destaining during 1 Hz stimulation was not consistent with Eqn 1 because fractional destaining was not constant. Instead, fractional destaining decreased substantially, by a factor of 2.7 ± 0.1 over the 25 min ($n = 7$ preparations; ***Figure 2C***, left panel, magenta line is the prediction if fractional destaining was constant).

For the analysis: $F(t)$ was estimated as the median fluorescence intensity of punctal regions of interest (ROIs; see ***Figure 2–Figure Supplement 4***) after subtracting the signal remaining after the final 20 Hz train. Fractional destaining was then estimated from short time intervals by dividing the slope of straight line fits of $F(t)$ during each interval (magenta lines in ***Figure 2B***) by $F(t)$ at the start of the same interval (green circles). Further analysis showed that the decrease evident in ***Figure 2C*** was not caused by technical errors related to baseline fluorescence loss seen in some preparations, or by flaws in the premise that the final 20 Hz train fully destains all recycling vesicles. Specifically: Correcting for the baseline fluorescence loss decreased the estimate of fractional destaining for later intervals (e.g., minute 21 - 25) more than for earlier intervals (e.g., minute 0 - 1.5), and, as a consequence, indicated an even greater decrease in the estimate over time; i.e., estimates of fractional destaining decreased by a factor of 4.4 ± 0.4 during the 25 min of 1 Hz stimulation after correcting (***Figure 2C***, right panel). Likewise, correcting for any error in the premise that the final 20 Hz train eliminated dye from all recycling vesicles could increase the factor even more, although any correction for this sort of error would be small.

Box 1. Multiple reserves can explain decrease in fractional destaining



Comparison of models with one reserve pool (left) and with two parallel reserve pools (right) that feed separate subdivisions of the readily releasable pool; wide arrows signify *fast-releasing* and narrow arrows signify *reluctant*. For both models, the number of stained vesicles within the readily releasable pools (RRPs) decreases over time of stimulation, accounting for the decrease in the absolute amount of destaining for each unit of time. However, with a single reserve pool, the ratio of stained fast-releasing to stained reluctant vesicles never changes, and, as a consequence, the *fractional destaining* at any point in time (see Results) does not change. In contrast, with two reserves, vesicle mobilization in path **a** is faster than in path **b**, causing path **a** to become exhausted sooner. As a consequence, the ratio of stained fast-releasing to stained reluctant vesicles decreases over time, resulting in decreased fractional destaining.

Next, an analysis of the individual ROIs showed that deviations from Eqn 1 occurred at almost all individual synapses despite variation between individuals in the details (***Figure 2–Figure Supplement 5***; see also ***Waters and Smith, 2002***). That is, measurement noise prevented applying the analysis in ***Figure 2B-C*** to many of the individuals. However, Eqn 1 is mathematically equivalent to the single exponential decay:

$$F(t) = F(0) \cdot e^{-k \cdot t} \tag{2}$$

where $F(0)$ is the fluorescence intensity at the start. And, the best fitting version of Eqn 2 for each individual could be compared to the full time course of each, acquired during the full 25 min of 1 Hz stimulation. This allowed a higher resolution analysis because the full time courses consisted of more data points than the short intervals used to calculate fractional destaining in ***Figure 2C***, making them less sensitive to measurement noise. Statistically significant deviations of $p < 0.05$ were detected for >90 % of individuals (5638 of 6252) in an analysis of residuals where k was allowed to vary freely between individuals (***Figure 2D***; see ***Figure 2–Figure Supplement 6*** for methodology, and ***Figure 2E*** for the analogous analysis at the level of preparations). This analysis shows that deviations from Eqn 1 occur at the level of individual synapses and rules out the concern that the decrease in fractional destaining evident in ***Figure 2C*** might have been caused by heterogeneity among the individuals.

Most individual ROIs and the collective behavior of populations could be fit with the weighted sum of two exponentials (***Figure 2–Figure Supplement 7***), although weighted sums of three or more exponentials and a variety of other functions could not be excluded. The result is consistent with models containing two or more reserve pools where the decrease in fractional destaining in ***Figure 2C*** would be caused by selective decrease in the number of stained vesicles in reserve

pools that are mobilized for exocytosis quickly, leaving the remaining dye predominantly trapped in vesicles that are mobilized for exocytosis slowly. ***Box 1*** illustrates this point with a model where the reserve pools operate in parallel (right panel, quickly mobilized vesicles in pathway **a** vs slowly mobilized in pathway **b**). However, further experiments, below, were still required to rule out alternatives where the reserve pools are instead connected in series, and a variety of other explanations for the decrease in fractional destaining that do not involve multiple reserve pools.

No recovery of fractional destaining during rest intervals

A key point is that mixing between the reserve pools would have to be slow during 1 Hz stimulation, if it occurs at all. Otherwise, mixing would have caused the stained vesicles in quickly and slowly mobilized reserve pools to equilibrate over the 25 min of 1 Hz stimulation, which would have prevented the decreases in fractional destaining. And indeed, further experiments showed that the decreases in fractional destaining did not reverse during long rest intervals (***Figure 3***).

Evidence against selective depletion of dye from readily releasable pools

One alternative to multiple reserve pools that needed to be ruled out was the possibility that the decrease in fractional destaining during 1 Hz stimulation in ***Figure 2B-C*** was caused by selective dye loss from readily releasable pools. Selective dye loss from readily releasable pools without multiple reserve pools seemed unlikely because spontaneous mixing between readily releasable and reserve pools is thought to occur on the order of one minute (***Murthy and Stevens, 1999***), which is fast compared to the destaining time course during 1 Hz stimulation in ***Figure 2B-C***. Nevertheless, to test this possibility, we stained synapses as above with FM4-64, but this time destained first with a 20 Hz train of 80 pulses followed immediately by 25 min of 1 Hz stimulation (diagram atop ***Figure 4A***). The 80 pulses at 20 Hz is enough to exhaust the readily releasable pools at these synapses (***Stevens and Williams, 2007***; ***Garcia-Perez et al., 2008***), but did not greatly alter fractional destaining measured during the subsequent 1 Hz stimulation (***Figure 4B***, compare blue circles to green rectangles). This result confirms that the decrease in fractional destaining seen during long trains of 1 Hz stimulation was not caused by selective depletion of dye from readily releasable pools.

For these experiments, we included a second 1 Hz train after a rest interval of 4 min (diagram atop ***Figure 4A***) to test if fractional destaining would recover during rest intervals after being driven to the minimum value. No recovery was seen (compare minute 29 - 33 to minute 21 - 25 in ***Figure 4B***, either panel). This result confirms the conclusion from ***Figure 3*** that decreases in fractional destaining induced by long trains of 1 Hz stimulation and measured during subsequent 1 Hz trains do not reverse quickly during rest intervals, if at all.

Evidence against explanations that do not involve multiple reserve pools

Next we rule out alternative explanations for the long-lasting decreases in fractional destaining that do not involve pools at all.

Long-term presynaptic depression: In principle, low frequency stimulation can induce long-term depression in presynaptic function that might cause fractional destaining to decrease even if there were only a single reserve pool. However, no long-term presynaptic depression was seen during 1 Hz stimulation when synaptic vesicle exocytosis was measured using vGlut1-synaptopHluorin fluorescence instead of FM4-64 (***Figure 5***).

The absence of long-term depression in vGlut1-synaptopHluorin fluorescence is compatible with the decrease in fractional destaining measured with FM4-64 because, unlike FM4-64, synaptopHluorin does not disassociate from vesicle membranes after exocytosis and therefore tracks presynaptic function through multiple rounds of exo/endocytosis (***Miesenböck, 2012***). Instead, the result argues against long-term presynaptic depression as a cause for the decrease in fractional destaining measured with FM4-64. We note, however, that the result does not contradict previous reports of presynaptic long-term depression where induction required postsynaptic depolarization

(***Goda and Stevens, 1996***) because postsynaptic depolarization was likely prevented in the present study by glutamate receptor antagonists.

Long-lasting switch to kiss and run: Alternatively, fractional destaining might decrease if endocytosis switched from the standard mode to a faster *kiss-and-run* mode, which sometimes is too fast to allow complete clearance of FM4-64 from the membrane of individual vesicles (***Klingauf et al., 1998***). This explanation seemed unlikely because the switch in timing of endocytosis would have to persist for minutes during rest intervals to account for the results in ***Figure 3*** and ***Figure 4***. Nevertheless, to test this, we conducted experiments similar to those documented in ***Figure 2***, except using the FM2-10 dye, which dissacociates from membranes more quickly than FM4-64, allowing faster clearance (***Klingauf et al., 1998***).

Despite the faster clearance, the decrease in fractional destaining during 1 Hz stimulaton was not altered (Figure 6, compare blue circles to green rectangles). The result does not rule out changes in the timing of endocytosis, but does argue that clearance was fast enough throughout our experiments to allow complete clearance of FM-dyes, even if changes occured. As a consequence, the result argues against changes in the timing of endocytosis as the cause of the decrease in fractional destaining seen above. Notably, the results are not directly comparable to earlier studies conducted in the absence of β-cyclodextrins (see ***Figure 2–Figure Supplement 1***).

The results in this section all support the hypothesis that the decrease in fractional destaining seen during long trains of 1 Hz stimulation is caused by selective depletion of a quickly mobilized pool of reserve vesicles because they rule out alternative explanations that have arisen. Remaining doubt is addressed, below, with affirmative evidence that multiple reserve pools are indeed present.

Faster destaining when staining is induced with low frequency stimulation

As a first step, we began by reasoning that vesicles reconstituted from recycled membrane during 1 Hz stimulation would have to be predominantly targeted back to the quickly mobilized reserve pool. Otherwise, targeting to the slowly mobilized reserve pool would have displaced already stained vesicles from the slowly to the quickly mobilized reserve pool, which would have prevented the decreases in fractional destaining seen above.

To test this, we stained vesicles during stimulation with 240 or 1200 pulses at 20 Hz or 240 pulses at 1 Hz in interleaved experiments. We then compared fractional destaining during subsequent 1 Hz stimulation. The experimental protocol is diagrammed in ***Figure 7A***.

Fractional destaining was greater when vesicle recycling had been driven by 1 Hz stimulation during the staining phase of the experiment (compare bar c to a and b in ***Figure 7B***), as expected if a larger fraction of the stained vesicles were targeted to a quickly mobilized reserve pool. Further experiments diagrammed in ***Figure 7C*** showed that 240 pulses at 20 Hz and at 1 Hz stain synapses to equivalent levels (***Figure 7D-F***), indicating that the greater fractional destaining seen after selectively staining vesicles that recycle during 1 Hz stimulation was not because fewer vesicles had been stained. Taken together, these results suggest that vesicles reconstituted from membrane that is recycled during ongoing 1 Hz stimulation are targeted predominantly to a quickly mobilized reserve pool. In contrast, vesicles reconstituted during 20 Hz stimulation are targeted to both quickly and slowly mobilized reserve pools. The information allowed us to design a method to stain quickly and slowly mobilized reserve pools with different colors.

Two color staining of separate reserve pools distinguished by mobilization timing

That is, we next confirmed the presence of multiple reserve pools with the experiment diagrammed atop ***Figure 8***. The idea was to stain the quickly and slowly mobilized pools with different colored dyes, and then monitor destaining of each color separately. To achieve this, we first stained all recycling vesicles with FM4-64 (red) using the standard 60 s of 20 Hz stimulation. Next, we partly destained with 1 Hz stimulation for 10 min. We reasoned that 1 Hz for 10 min would nearly completely destain any quickly mobilized reserve pool because it was enough to drive fractional destaining to close to the minimum value in ***Figure 2B-C***, and elsewhere. We then partly re-stained the synapses

with FM1-43 (green), but this time by stimulating at 1 Hz, which we reasoned would predominantly re-stain quickly mobilized reserves based on the results in ***Figure 7B***. For this second staining phase, we chose a duration of 5 min, which was calculated from experiments, above, so that the number of vesicles stained with the new (green) stain would be similar to the number, stained in red, remaining from the first staining phase. Finally, we destained both colors: first with 1 Hz stimulation to measure fractional destaining; and then with 20 Hz stimulation to fully destain both quickly and slowly mobilized reserves as usual.

As predicted, the green stain applied during 1 Hz stimulation destained >4-fold faster than the red stain applied during the initial 20 Hz stimulation (***Figure 8A***). The results were reversed when vesicles were stained first with green at 20 Hz and second with red at 1 Hz (***Figure 8B***). And, finally, ***Figure 8C*** confirms that the number of stained vesicles at the start of the destaining phase of the experiment was similar for the two colors.

These results show that reserve synaptic vesicles are segregated into at least two pools that can be distinguished by the timining of mobilization during 1 Hz stimulation. The one remaining caveat is that the results so far do not rule out *last-in/first-out* models where reserve vesicles are stored in a single pool with constituents that inter-mix slowly, if at all, during 1 Hz stimulation (***Rizzoli and Betz, 2004***; ***Kamin et al., 2010***; see ***Figure 8–Figure Supplement 1***). However, all serial models - which include single pool last-in/first-out models - would require fast mixing either between or within reserve pools during 20 Hz stimulation to account for the results in ***Figure 7B*** and ***Figure 8***. And, this is ruled out, below.

Mixing continues to be slow/absent near body temperature

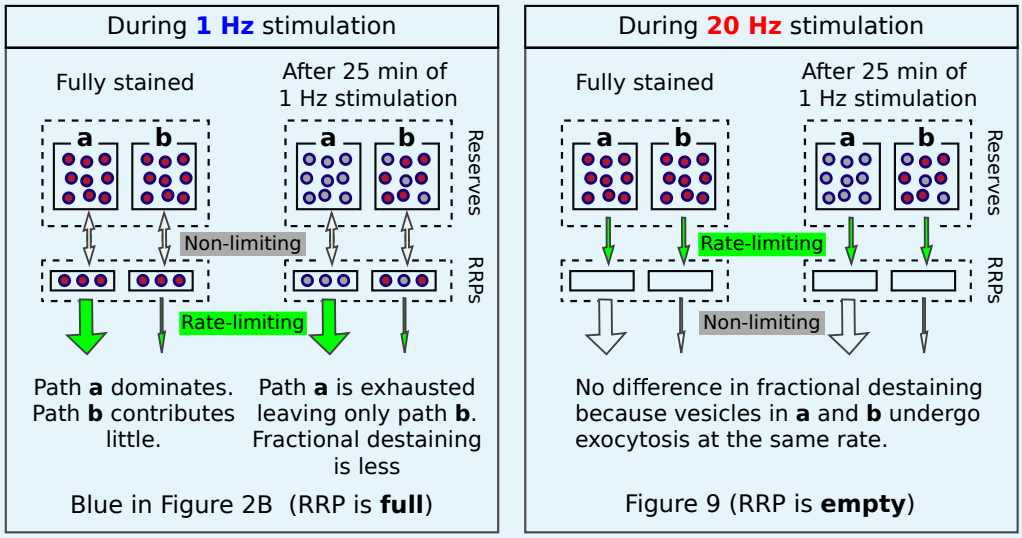
The experiments above were conducted at room temperature, and there is evidence that vesicles in the interiors of synaptic terminals are more motile at body temperature (***Westphal et al., 2008***; ***Kamin et al., 2010***; ***Lee et al., 2012***; ***Park et al., 2012***). It is not known if the motility is related to rate-limiting steps in synaptic vesicle trafficking that would influence the timing of mobilization. However, the decrease in fractional destaining during 1 Hz stimulation and the absence of mixing during rest intervals were both preserved at 35 C (***Figure 8–Figure Supplement 2*** and ***Figure 8–Figure Supplement 3***).

Parallel mobilization

To distinguish between serial and parallel processing of the two types of reserves, we begin by showing that decreases in fractional destaining were absent when stimulation was 20 Hz (***Figure 9A*** and bars labeled b-d in ***Figure 9C***). And, 25 min of 1 Hz stimulation had almost no impact on the timing of destaining when subsequent stimulation was 20 Hz (***Figure 9B***, and bars labeled f and g vs bars b and c, respectively, in ***Figure 9C***). The absence of a large impact was striking because fractional destaining would have been decreased by a factor of ∼4 if measured instead during 1 Hz stimulation, as shown in multiple experiments above. These results suggest that the distinction between quickly and slowly mobilized reserves seen during 1 Hz stimulation is no longer evident when stimulation is 20 Hz.

To test this, we compared destaining during 1 Hz stimulation following conditioning with either 10 min of 1 Hz stimulation (***Figure 10A***), or 20 s of 20 Hz stimulation (***Figure 10B***). Both conditioning trains destained the synapses by about 50 %, but only the 1 Hz train caused a decrease in fractional destaining measured during the subsequent 1 Hz stimulation (insets of ***Figure 10A & B***, quantified in ***Figure 10C***). Taken together, these results demonstrate that vesicles in the two types of reserve pools are mobilized for exocytosis with equivalent timing when stimulation is 20 Hz, whereas vesicles in quickly mobilized reserve pools are mobilized for exocytosis >4 fold faster than vesicles in slowly mobilized reserve pools when stimulation is 1 Hz. The finding explains why short trains of 20 Hz stimulation stained both quickly and slowly mobilized vesicles whereas 1 Hz stimulation selectively stained quickly mobilized vesicles in ***Figure 7*** and ***Figure 8***.

Box 2. Different rate-limiting mechanisms at 1 vs 20 Hz



Wide arrows signify *fast-releasing* and narrow arrows signify *reluctant* readily releasable vesicles. The absence of rundown in fractional destaining when stimulating is 20 Hz (right panel) is in-line with parallel models, as diagrammed above, because: (1) 20 Hz stimulation is intense enough to quickly drive both fast-releasing and reluctantly-releasing components of the readily releasable pool (RRP) to a near-empty steady state; after which, (2) exocytosis is rate-limited by the timing of recruitment of reserve vesicles to vacant space within the RRPs (***Wesseling and Lo, 2002***; ***Garcia-Perez and Wesseling, 2008***; ***Garcia-Perez et al., 2008***; ***Raja et al., 2019***) instead of by mechanisms that determine probability of release of already releasable vesicles; and, finally (3) the timing of recruitment is the same for fast and reluctantly releasing subdivisions (***Garcia-Perez and Wesseling, 2008***; ***Mahfooz et al., 2016***; see ***Wesseling, 2019*** for a discussion of discrepancies reported for other synapse types).

The finding fits with core principles of parallel models, which predict that the decrease in fractional destaining would be occluded within seconds after the onset of stimulation at 20 Hz because the rate-limiting step in vesicle mobilization would shift upstream from catalysis of exocytosis to recruitment of reserve vesicles to the newly vacant readily releasable pool (see ***Box 2***). However, an additional experiment was still needed to rule out serial models where 20 Hz stimulation activates a mechanism that quickly mixes together vesicles in the quickly and slowly mobilized reserve pools (or within a single last-in/first-out pool).

Such a mixing mechanism seemed unlikely because it would have to be complete within a few seconds to account for the absence of a noticeable rightward shift in the time course of destaining during 20 Hz stimulation when initiated after 1 Hz trains had already selectively destained the quickly mobilized reserve vesicles (i.e., left panel ***Figure 9–Figure Supplement 1***). To test for a mixing mechanism in a way that would be conclusive, we destained synapses by: first stimulating at 1 Hz for 10 min to selectively destain the quickly mobilized vesicles; followed by 12 s at 20 Hz to activate any mixing mechanisms; and then again at 1 Hz to measure any effect on fractional destaining (see diagram atop ***Figure 10D***). ***Figure 10–Figure Supplement 2*** confirms that fractional destaining caused by 12 s of 20 Hz stimulation was not altered by long trains of 1 Hz stimulation, confirming that any mixing mechanism would have to have been fully active. Nevertheless, fractional destaining measured during the second 1 Hz train remained reduced, with no indication of any recovery (***Figure 10E***). This combination of results rules out activity-dependent mixing between quickly and slowly mobilized reserves, and, as a consequence, rules out any of the remaining serial models (i.e.,

any that are consistent with the results in ***Figures 2 - 9***).

In contrast, parallel models do predict the absence of recovery in fractional destaining in ***Figure 10D-E*** because the mechanism that causes the decrease during 1 Hz stimulation - i.e., selective depletion of dye from the quickly mobilized reserve - would quickly become fully relevant again as soon as the readily releasable pool had been replenished (i.e., within tens of seconds; ***Garcia-Perez and Wesseling, 2008***). Taken together, these results demonstrate that quickly and slowly mobilized reserve pools are processed in parallel.

Modeling

Finally, our working model, which is a specific type of parallel model, could fit the full spectrum of results in the present report using previously estimated values for rate-limiting vesicle trafficking parameters (see ***Appendix 1***). The exercise confirmed that parallel models can account for experimental details throughout the present study, but, given the number of parameters with otherwise unconstrained values, did not by itself provide new support for any specific parallel model. And indeed, the generic parallel model diagrammed in ***Box 1*** and ***Box 2*** could fit the results equally well.

Discussion

Synaptic vesicle trafficking in presynaptic terminals is central to brain function and is an increasingly important target of anti-epilepsy medicines (***Lyseng-Williamson, 2011***). A more detailed understanding might generate insight into the first principles underlying biological computation, and might aid second generation drug discovery (***García-Pérez et al., 2015***). Here we show that quickly and slowly mobilized reserve pools of vesicles are present in hippocampal synapses, and that the two types are mobilized for exocytosis in parallel, rather than in series as previously assumed.

The experiments were designed to test predictions of our working model of synaptic vesicle trafficking in presynaptic terminals (***Figure 1D***), which emerged from two separate lines of inquiry. The first line argued against the concept that mass action of reserve vesicles influences the timing of vesicle recruitment to the readily releasable pool (***Stevens and Wesseling, 1999b***; ***Garcia-Perez et al., 2008***; see ***Miki et al., 2020*** for a recent complementary type of evidence), while nevertheless supporting the often-linked concept that depletion of reserve pools is one of the mechanisms that causes short-term synaptic depression during extensive stimulation (***Gabriel et al., 2011***). The second line supported the concept that fast- and reluctantly-releasing readily releasable vesicles differ because they are docked to distinct types of release sites rather than because they are at distinct stages of biochemical priming (***Wesseling and Lo, 2002***; ***Garcia-Perez and Wesseling, 2008***; ***Mahfooz et al., 2016***; ***Raja et al., 2019***; see also ***Hu et al., 2013***; ***Böhme et al., 2016***; ***Akbergenova et al., 2018***; ***Maschi and Klyachko, 2020***; ***Li et al., 2021***; ***Karlocai et al., 2021***; ***Gou et al., 2022***).

A key point is that the present conclusion that quickly and slowly mobilized reserve vesicles are processed in parallel does not depend on either line of inquiry - or on our working model - and the evidence against serial models would continue to be equally strong even if questions arose about the previous conclusions. Nevertheless, we do view the present result as intriguing support for our working model because: (1) the opposite conclusion - that reserves are processed in series as widely assumed until now - would have caused us to reject the model; and, (2) no alternative parallel model has yet been proposed.

Absence of mixing

Notably, our working model contains a slow undocking mechanism operating continuously at ~1 /min that would have been consistent with slow mixing between quickly and slowly mobilized reserves if the undocked chains of vesicles were to mix freely (***Gabriel et al., 2011***). Because of this, the model did not anticipate the complete absence of recovery in fractional destaining over 8 min-long rest intervals in ***Figure 3***. However, the absence of mixing does not argue against our working model (see ***Appendix 1***) because chains of vesicles might be attached to a stable cytoskeletal scaffold that would be preserved after undocking, or might reside within a liquid phase gel that

prevents intermixing (*e.g.*, ***Siksou et al., 2007***; ***Fernández-Busnadiego et al., 2010***; ***Cole et al., 2016***; ***Milovanovic et al., 2018***).

Relationship to a deep reserve

The present results do not rule out the possibility that other types of synapses additionally or instead harbor a variety of reserve pools that are connected in series (***Neves and Lagnado, 1999***; ***Richards et al., 2003***). And indeed, the present results only pertain to the vesicles that are mobilized during 60 s of 20 Hz stimulation, whereas many vesicles within hippocampal presynaptic terminals are mobilized much more slowly, if at all during this time (***Harata et al., 2001***). We refer to the vesicles that are not mobilized in the time frame of minutes as the *deep reserve*. One possibility is that deep reserve vesicles do mix slowly with one or both of the quickly and slowly mobilized reserves identified above (***Denker et al., 2011***). This might account for the timing information in ***Rey et al.*** (***2015***) where vesicles that were recycled more recently were mobilized for exocytosis earlier over 10 ′s of min, although very slow mixing between the quickly and slowly mobilize reserve pools identified above cannot be ruled out either.

Relation to multiple classes of vesicles

The experiments in the present study were designed to measure vesicle exocytosis involved in action potential evoked release, whereas transmitter released spontaneously is thought to be stored in a different class of vesicles (***Kavalali, 2015***).

The present results are consistent with the possibility that the decision about whether a recycling vesicle will ultimately become reluctant or fast-releasing upon entering the readily releasable pool is made earlier, at the time of entry into the reserve pool. Alternatively, the parallel mobilization of slow and fast reserves might be analogous to current ideas about parallel cycling of vesicles involved in spontaneous release, which would then require multiple classes of vesicles (***Raingo et al., 2012***). However, adding the concept of multiple classes of vesicles could not replace the requirement for multiple classes of release sites because, otherwise, the readily releasable pool would eventually fill with reluctantly releasable vesicles during low frequency stimulation, which would result in long-lasting depression that was not seen in experiments designed to test this (see ***Figure 5***).

Multiplexed frequency filtering

Finally, our working model explains slowly mobilized reserves as a logical consequence of multiple classes of release sites, with no functional significance of their own. However, the variation among synapses documented in ***Figure 2–Figure Supplement 5*** might nevertheless be relevant for understanding biological computation.

That is, it has already been noted that inefficient release sites that engender reluctantly releasable components of the readily releasable pool would function as high-pass/low-cut frequency filters when transmitting information encoded within presynaptic spike trains, whereas efficient release sites engendering fast-releasing components would function as low-pass/high-cut filters (***Mahfooz et al., 2016***). The presence of multiple types of release sites might therefore endow individual synapses with a mechanism for selectively transmitting multiple types of frequency information while filtering out other types, which is analogous to the concept of *multiplexing* in digital information technology. The variation among synapses in ***Figure 2–Figure Supplement 5*** suggests that synapses *in vivo* likely contain the machinery for modulating multiplexing, which might provide a means for storing more information than modulating only the synaptic connection strength evident during low frequency use (***Bartol et al., 2015***). Notably, we previously observed extensive variation between calyx of Held synapses in *ex vivo* tissue in the ratio of fast-releasing to reluctant readily releasable vesicles, which, when taken together with the present results, suggests that mechanisms for modulating multiplexing might be present at a wide range of synapse types (***Mahfooz et al., 2016***).

Methods and Materials

Cell culture and imaging methods were similar to ***Raja et al.*** (***2019***).

Imaging: Imaging was performed 11-21 days after plating at 0.25 Hz, using a CCD camera (Photometrics CoolSnap HQ), and 25X oil objective (Zeiss 440842-9870), except where indicated. Focal drift was avoided in most experiments by clamping focal distance by feeding back the signal from a distance sensor attached to the objective (Physik Instrumente D-510.100, ~1 nm resolution) to a piezoelectric objective drive (MIPOS250, PiezosystemJena). For most experiments, FM4-64 was imaged with a green LED (530 nm; 50 ms exposures) via the XF102-2 filter set from Omega. When used in combination with FM1-43, FM4-64 was instead imaged with an amber LED (590 nm; 1 s exposures) via a custom set containing band pass excitation filter FB600-10, dichroic DMLP638R, and long-pass emission filter FELH0650, all from Thorlabs. FM1-43 was imaged with a blue LED (470 nm; 200 ms exposures) via the XF100-2 filter set from Omega and FM2-10 was imaged with the same blue LED (200 ms exposures), but with the XF115-2 filter set from Omega. vGlut1-synaptopHluorin (***Voglmaier et al., 2006***) was expressed by infecting at day 7 after plating with an AAV1 construct and imaged with the blue LED via the XF116-2 filter set from Omega; exposure length was 200 ms except for ***Figure 5A*** where exposure length was 300 ms and the objective was 60X (Olympus UPlanFL N) rather than 25X. LEDs were all Luxeon Star and were driven with 700 mA of current. Bathing solution was exchanged continuously during imaging at 0.2 – 0.5 ml/min within a sealed chamber holding ~35 μL. Heating to 35 C was monitored with a bead thermistor (Warner, TA-29) built into the chamber, and exposed to the extracellular solution. Electrical stimulation was bipolar (0.5 ms at - 30 V then 0.5 ms at + 30 V) *via* two platinum electrodes built into the chamber. Neurotransmitter receptors were blocked with (in μM): picrotoxin (50); DNQX (10); and DL-APV (50). Other solutes were (in mM): NaCl (118); KCl (2); Ca^{2+} (2.6); Mg^{2+} (1.3); Glucose (30); and HEPES (25). FM4-64 and FM1-43 were used at 15 µM, and FM2-10 at 100 µM. Advasep-7 and Captisol were purchased from Cydex Pharmaceuticals or graciously provided as samples and used at 1 mM during the destaining phase of FM-dye experiments and throughout experiments using vGlut1-synaptopHluorin.

Processing: Time lapse images were aligned and Regions of Interest (ROIs) identified as described in ***Raja et al.*** (***2019***) (see ***Figure 2–Figure Supplement 4***). Between 175 and 1773 ROIs were detected for each field of view. For summary statistics, the median values from a single field of view/experiment were counted as n = 1 unless otherwise indicated.

Normalization: For comparing images across preparations, median or individual ROI values were: divided by the mean value of the background region and then normalized by the baseline signal, except where indicated.

Curve fitting: The Matlab code for identifying the best fitting single exponential was:

```
function k = GetBestSingleExp(DcyDat, dpmin)
    s = fitoptions('Method','NonLinearLeastSquares',...
                   'Lower', 0, 'Upper', 0.3, 'Startpoint', -0.002);
    f = fittype('exp((k*-1)*t)','options',s, 'independent', 't');
    Time = (0:(length(DcyDat)-1))/dpmin;
    cfun = fit(Time',DcyDat,f);
    k = cfun.k;
```

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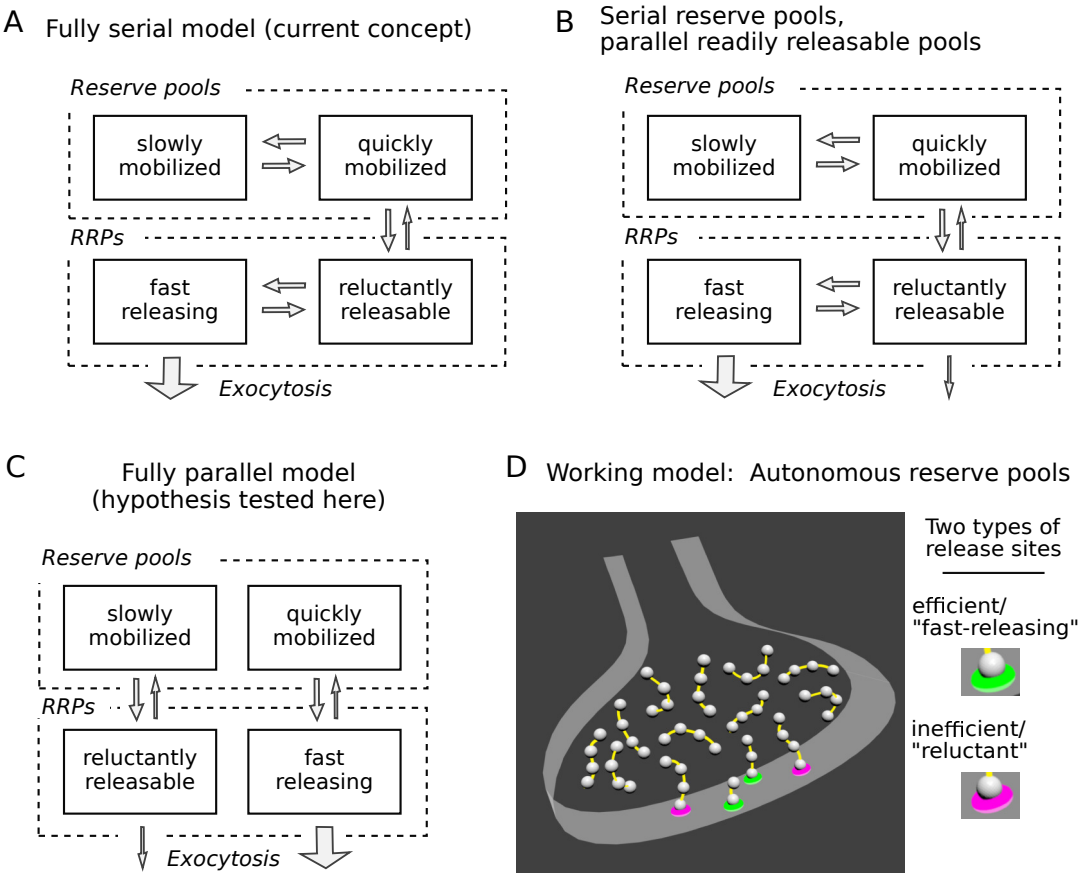


Figure 1. Three possible organizations for synaptic vesicle pools; *RRPs* signifies readily releasable pools. **(A)** The predominant view currently seems to be that all pools are connected in series as depicted. **(B & C)** However, recent evidence indicates that reluctant and fast-releasing subdivisions of the readily releasable pool can be released in parallel. **(D)** And, a separate line of evidence suggested that each readily releasable vesicle is associated with an autonomous reserve, implying that slowly and quickly mobilized reserves may also be processed in parallel, as depicted in **Panel C**.

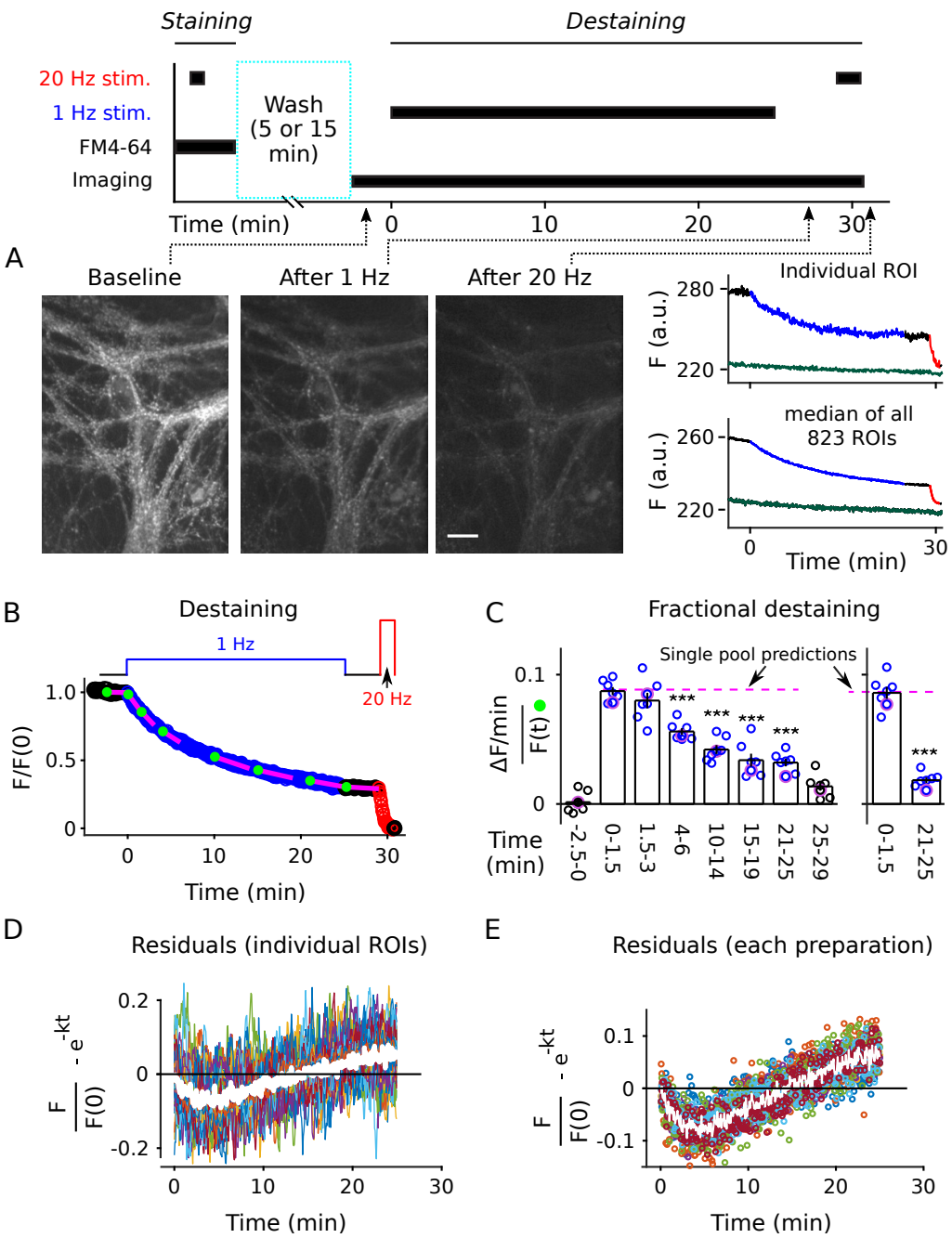


Figure 2. Analysis of FM4-64 destaining during 25 min of 1 Hz stimulation. Synapses were stained with 60 s of 20 Hz electrical stimulation in the presence of dye here and in subsequent experiments except where indicated. **(A)** Each image is the mean of 20 sequential raw images. Scale is 20 µm. The traces pertain to the same experiment; the lower trace (green/blue) in each plot is background; *F (a.u.)* signifies arbitrary units of fluorescence. Destaining is color coded in blue for 1 Hz stimulation and red for 20 Hz here and throughout, except where indicated. **(B)** Mean ± s.e.m. of median values versus time for $n = 7$ preparations; error bars are smaller than the symbols. See **Methods** for automatic detection of ROIs and formula for averaging across preparations. **(C)** Fractional destaining for a variety of time intervals; the values were calculated by dividing the slopes of the magenta lines by the values of the preceding green circles in **Panel B**. Wine-colored annuli indicate measurements from example in **Panel A**. Rightmost two bars are after subtracting the baseline value measured either immediately before (minute −2.5 - 0) or immediately after (minute 25 - 29) 1 Hz stimulation. The dashed magenta line is the value expected from models with a single, quickly mixing reserve pool (*** signifies $p < 0.001$; rank sum). **(D)** Representative residual values for individual ROIs after subtracting the best fitting single exponential. For clarity, values for only 100 of 6252 ROIs are plotted, but were chosen at random after excluding outliers with maximum deviation from zero of > 0.25 (outliers were 23 % of total). Plots were smoothed by taking a moving average of the raw residuals with a sliding window of 5. The white line is the mean of the entire data set, including outliers. **(E)** Residual values for all seven preparations, white line is the mean.

Figure 2–Figure supplement 1. Equivalent destaining for FM4-64 and FM2-10 in presence of Captisol.
Figure 2–Figure supplement 2. Analysis of FM4-64 signal remaining after 20 Hz stimulation for 100 s.
Figure 2–Figure supplement 3. No evidence for photobleaching.
Figure 2–Figure supplement 4. Graphical user interface for semi-automatic ROI detection.
Figure 2–Figure supplement 5. Heterogeneity among synapses.
Figure 2–Figure supplement 6. Procedure for calculating residuals after fitting with a single exponential.
Figure 2–Figure supplement 7. Double exponential fit during 1 Hz stimulation.

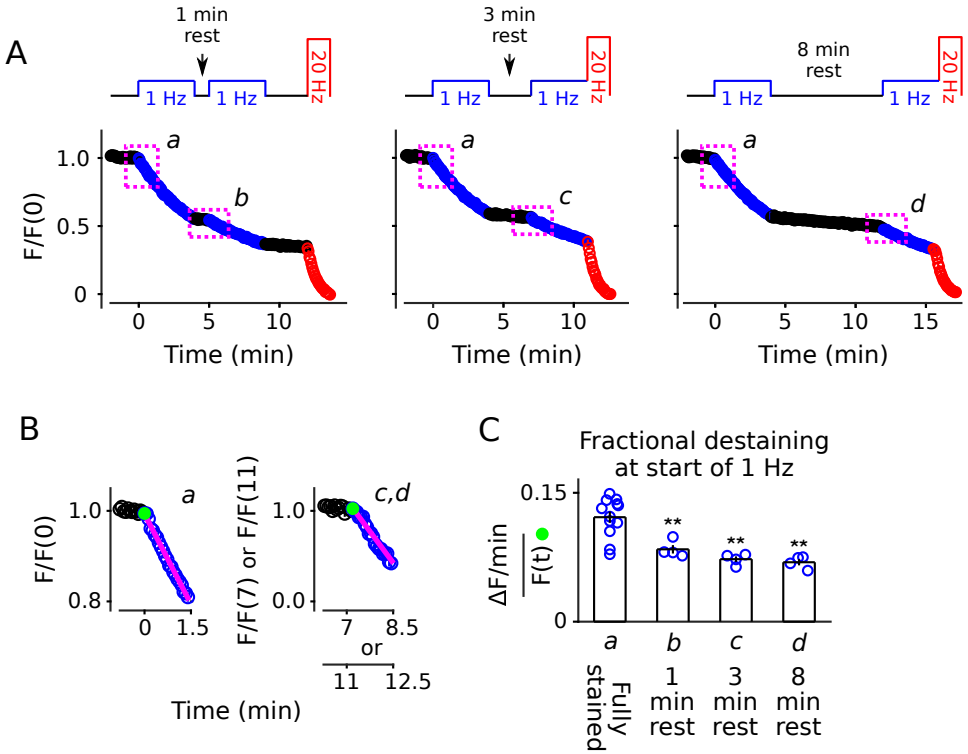


Figure 3. Decrease in fractional destaining induced by 1 Hz stimulation persists during long rest intervals. **(A)** Comparison of destaining during two 4 min-long trains of 1 Hz stimulation separated by 1 min, 3 min and 8 min. **(B)** Replots of the first 1.5 min of destaining (magenta dashed boxes in **Panel A**) during 1 Hz stimulation at fully stained synapses (**a**); or after $\geq$ 3 min of rest following 4 min of 1 Hz stimulation (**c,d**). The fragments of the destaining time courses for **c & d** were renormalized by the immediately preceding rest interval to illustrate that fractional destaining was substantially less during the second 1 Hz trains. Magenta lines and green circles are slope and initial intensity as in ***Figure 2B***. **(C)** Fractional destaining at the start of each 1 Hz train, calculated by dividing the slopes of the magenta lines by the values of the preceding green circles in **Panel B**, matching the calculation in ***Figure 2C***. ** signifies $p < 0.01$ (rank sum).

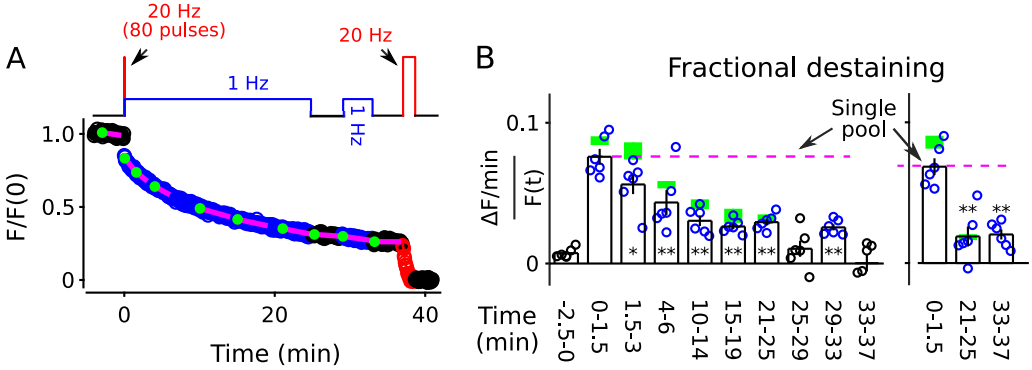


Figure 4. FM4-64 destaining during 25 min of 1 Hz stimulation immediately following 4 s of 20 Hz stimulation. Decrease in fractional destaining over time in **Panel B** is similar to when the initial 4 s of 20 Hz stimulation is omitted - green rectangles are mean ± s.e.m. from ***Figure 2C*** - ruling out selective depletion of the readily releasable pool as the cause of the decrease. Rightmost three bars are after subtracting the baseline value measured either immediately before (minute −2.5 - 0) or immediately after (minute 25 - 29) or both immediately before and after (minute 25 - 29 and minute 33 - 37) 1 Hz stimulation. The dashed magenta line is the value expected from models with a single reserve pool where fractional destaining is constant (* signifies $p < 0.05$ and ** signifies $p < 0.01$; rank sum).

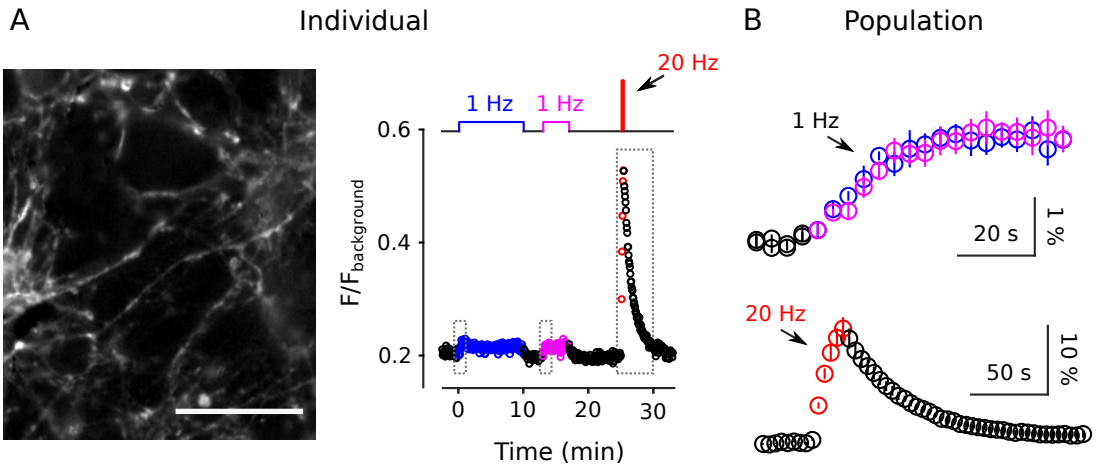


Figure 5. No long-term depression during 1 Hz stimulation when measured with vGlut1-SynaptopHluorin. Synapses were stimulated with two trains of 1 Hz electrical stimulation followed by 20 s of 20 Hz. **(A)** Example from a single preparation. The image is the mean of 20 sequential raw images starting with the start of 20 Hz stimulation; scale bar is 20 µm. The plot is the corresponding fluorescence signal from the entire experiment. **(B)** Mean changes in fluorescence intensity from $n = 6$ fields of view at the start of the two 1 Hz trains showing no difference (top, blue is first train, magenta is second), and during the 20 Hz train (bottom, red). For these experiments, fluorescence intensity was only measured over short intervals spanning the onset of 1 Hz stimulation and the 20 Hz train corresponding to the dashed boxes in **Panel (A)** - rather than during the entire experiments - to avoid photobleaching. Baseline intensity values immediately before the onset of stimulation were subtracted before combining across experiments. $\frac{\Delta F}{F}$ was 1.7 $\pm$0.2 % at the start of the first and 1.9 $\pm$0.2 % at the start of the second 1 Hz trains. Scale bars are $\frac{\Delta F}{F}$ versus time. The individual in **Panel (A)** was acquired using more light exposure (see Methods), and was part of a larger data set where a small amount of photobleaching (~15 %) did occur over the 10 min of 1 Hz stimulation.

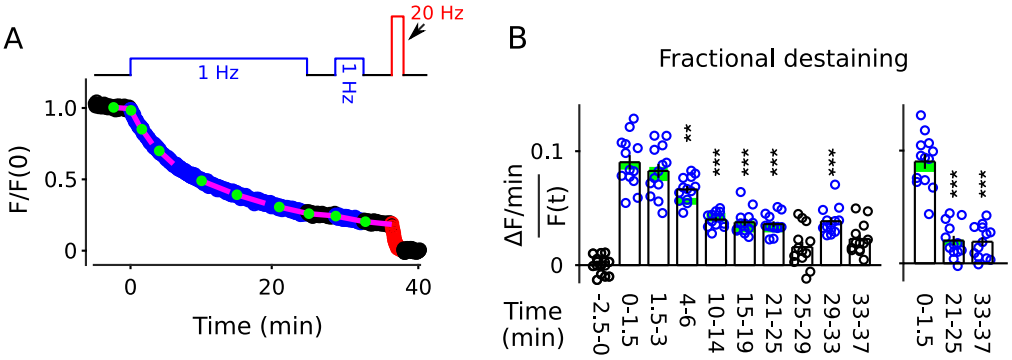


Figure 6. FM2-10 destaining; Similar to ***Figure 2B-C*** except synapses were stained with FM2-10 instead of FM4-64 ($n = 13$ preparations). **(A)** Time course. **(B)** Analogous to ***Figure 2C***. Green rectangles are mean ±s.e.m. from ***Figure 2C***. Values for rightmost 3 bars were calculated by subtracting background fractional destaining values as in ***Figure 4B***.

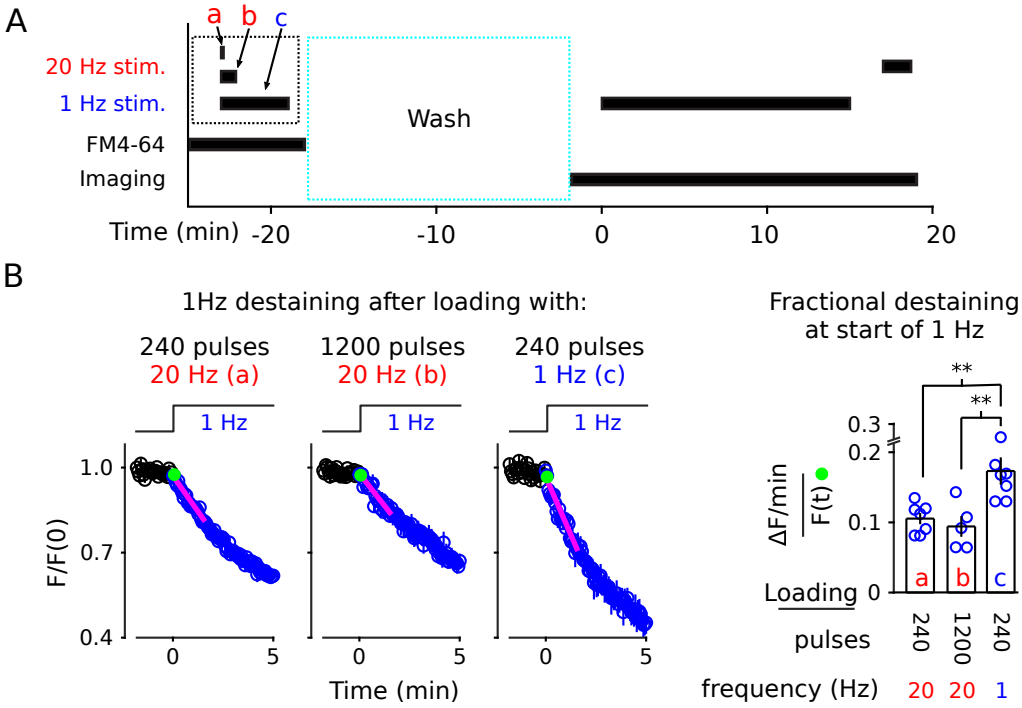


Figure 7. 1 Hz destaining is faster after loading at 1 Hz compared to at 20 Hz. **(A)** Experimental protocol. The experimental variables are the frequency and duration of stimulation during the staining phase of the experiment (i.e., **a**, **b**, and **c**), which is different from the previous experiments. **(B)** FM4-64 destaining during the first 5 min of 1 Hz stimulation after loading with 1 Hz or 20 Hz stimulation; see ***Figure 7–Figure Supplement 1*** for full destaining time courses. Magenta lines and green circles are slope and initial intensity as in ***Figure 2B*** ($n \geq 5$; ** signifies $p < 0.01$, rank sum).

Figure 7–Figure supplement 1. Full destaining time courses for experiments in **Panel B**.

Figure 7–Figure supplement 2. Similar amount of staining induced by 240 pulses at 1 vs 20 Hz

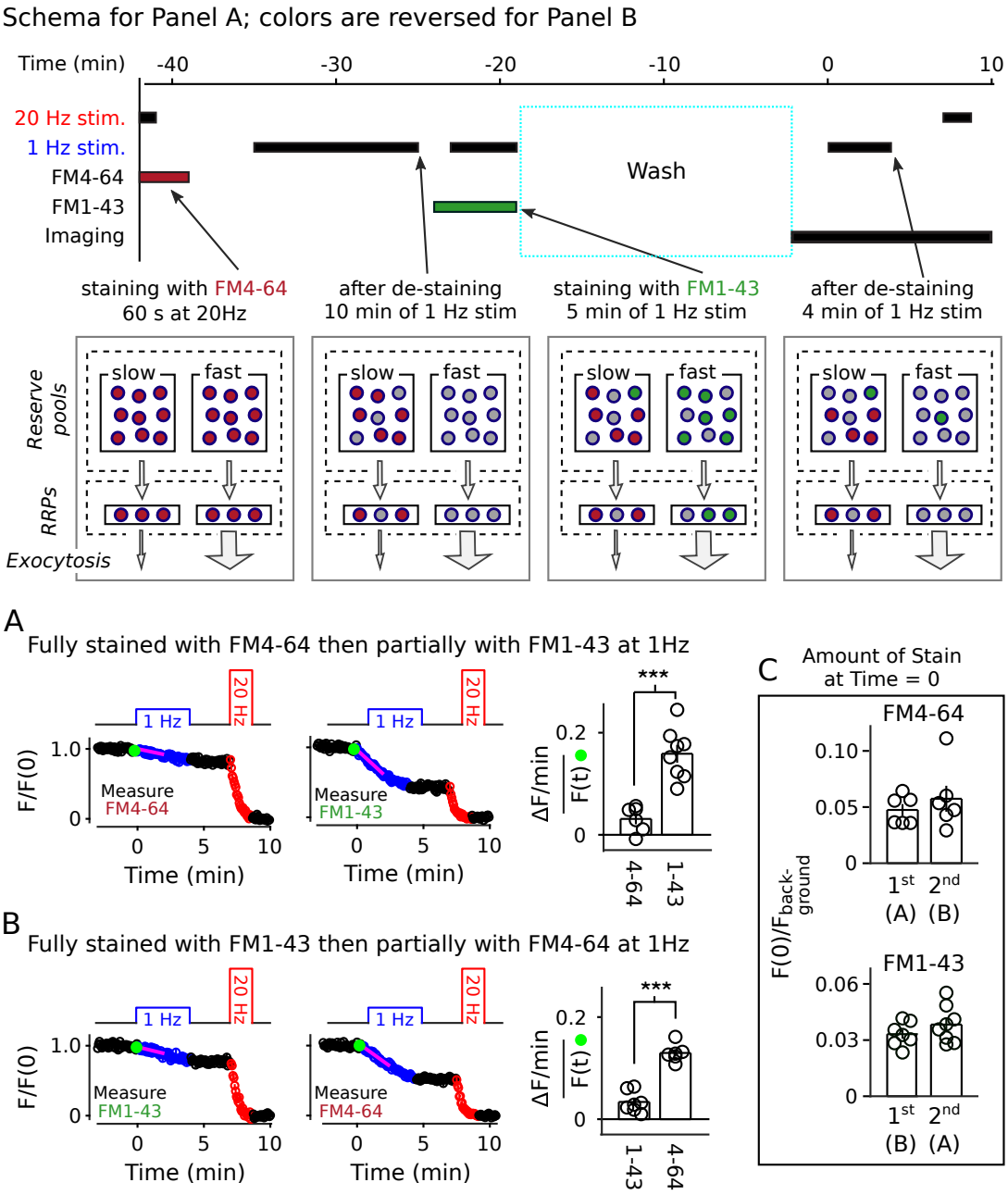


Figure 8. Two color separation of reserve pools. The experimental design is diagrammed at top, and is described in the Results; *RRPs* signifies readily releasable pools. **(A)** Slowly mobilized reserve is labeled with FM4-64 (red) and quickly mobilized is labeled with FM1-43 (green). **(B)** Analogous to **Panel A**, except the colors are reversed. **(A & B)** Magenta lines and green circles are slope and initial intensity as in ***Figure 2B***. **(C)** Similar amounts of stain for each dye when applied first during 20 Hz stimulation, and then partially destained with 1 Hz stimulation, or when applied second during 1 Hz stimulation.

Figure 8–Figure supplement 1. Description of last-in/first-out models

Figure 8–Figure supplement 2. FM4-64 destaining at 35 C.

Figure 8–Figure supplement 3. Two color experiment at 35 C.

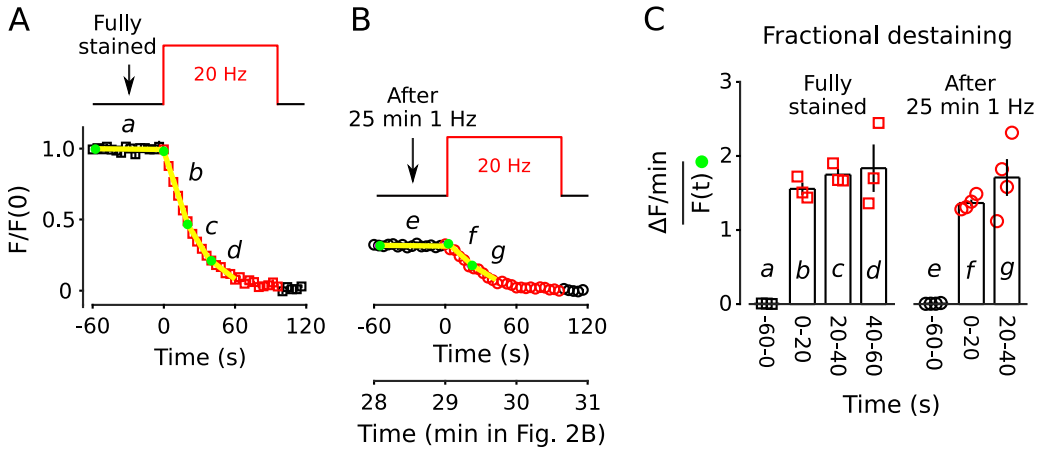


Figure 9. No decrease in fractional destaining when stimulation is 20 Hz. **(A)** Synapses were first stained with FM4-64 by stimulating at 20 Hz stimulation for 60 s as above then destained with a single train of 20 Hz stimulation as diagrammed at top ($n = 3$). Yellow lines and green circles are slope and initial intensity, analogous to the magenta lines and green circles in ***Figure 2B*** and elsewhere. **(B)** Destaining time course after 25 min of 1 Hz stimulation; data are a subset of data plotted in ***Figure 2B***; $n = 4$ instead of the 7 in ***Figure 2*** because the criterion of $\leq 1.5\,\%$ destaining per min before stimulation was calculated from the rest period following the 1 Hz stimulation when the remaining stain was 3-fold less. The experiments in **Panels A & B** were interleaved. **(C)** Fractional destaining during 20 Hz stimulation showing no decrease over time (e.g., compare to ***Figure 2C***). Note that the time intervals for calculating fractional destaining are 20 s versus $\geq$1.5 min elsewhere (i.e., because elsewhere stimulation was 1 Hz and destaining was slower).

Figure 9–Figure supplement 1. Overlaid plots of destaining during 20 Hz stimulation.

Figure 9–Figure supplement 2. Further evidence that the decrease in fractional destaining is absent during subsequent 20 Hz stimulation.

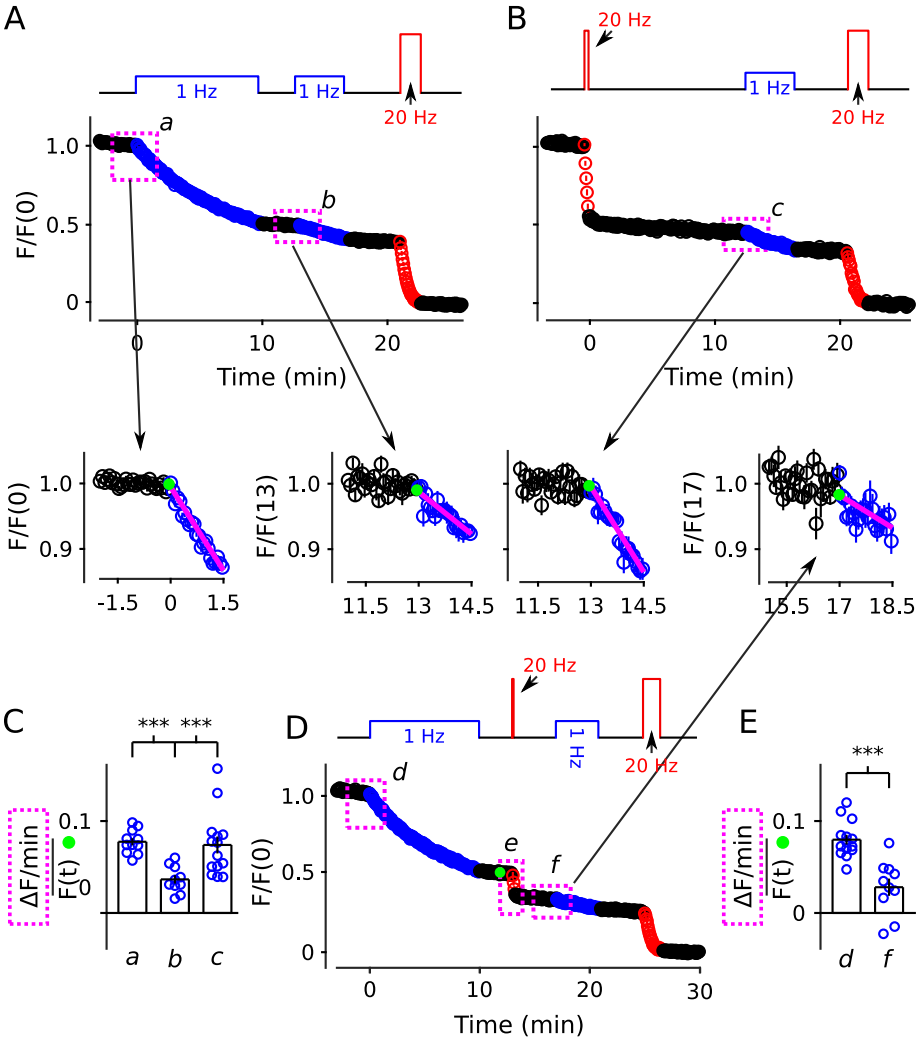


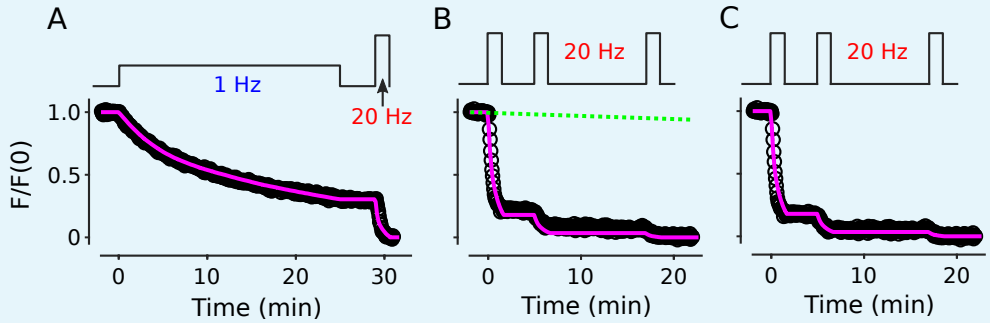
Figure 10. 20 Hz stimulation does not induce or reverse decreases in fractional destaining induced and measured during 1 Hz stimulation. Synapses were first stained with FM4-64 by stimulating at 20 Hz stimulation for 60 s as above. Magenta lines and green circles are slope and initial intensity as in ***Figure 2B*** and elsewhere. **(A & B)** Synapses were destained 50 % with either 1 Hz (**Panel A**, $n = 11$) or 20 Hz (**Panel B**, $n = 8$) stimulation, followed by a second train at 1 Hz. Insets are destaining during the first 1.5 min of the 1 Hz trains after normalizing by $F(t)$ during the the preceding rest interval. The inset corresponding to magenta box c in **Panel B** summarizes results from $n = 14$ preparations, including the $n = 8$ in **Panel B** and $n = 6$ more from ***Figure 10–Figure Supplement 1A*** where the first 20 Hz train was delayed by 10 min. **(C)** Quantification of fractional destaining - calculated as in ***Figure 2C*** - during the first 1.5 min of 1 Hz stimulation in **Panels A & B** (*** signifies $p < 0.001$; rank sum). The graph shows that fractional destaining during the second train was reduced when the preceding train was at 1 Hz (a vs b), but not when at 20 Hz (a vs c). The result confirms that 20 Hz stimulation depletes dye from quickly and slowly mobilized reserves with equivalent timing. **(D)** Synapses were destained with 10 min of 1 Hz stimulation followed by 12 s of 20 Hz stimulation, then another 4 min of 1 Hz stimulation ($n = 13$). **(E)** Quantification of fractional destaining during the first 1.5 min of 1 Hz stimulation in **Panel D** showing that the 20 Hz stimulation did not reverse the decrease in fractional destaining induced by the first 1 Hz train and measured during the second. Fractional destaining in box marked e in **Panel D** is quantified in ***Figure 10–Figure Supplement 2***.

Figure 10–Figure supplement 1. Formal control for matching **Panels A & B**

Figure 10–Figure supplement 2. 1 Hz train in **Panel D** does not alter fractional destaining at **e**.

Appendix 1

Destaining time courses fit with working model in *Figure 1D*



Appendix 1 Figure 1. Magenta lines are the simulation with three types of release sites with $p_{rs} = 0.28$ (7 %), 0.025 (33 %), and 0.0025 (60 %) **(A)** Replot of results in ***Figure 2B*** confirming that the model is consistent with FM-dye destaining when stimulation is 1 Hz. **(B)** Replot of results in the left panel of ***Figure 2–Figure Supplement 2A*** after re-normalizing so that the final points have a value of 0. The near-miss of the magenta illustrates how highly constrained the model is for destaining during 20 Hz stimulation since there are essentially no free parameters. The green line is the estimated stimulation-independent rundown of 0.25 %/min. **(C)** Replot after correcting for the rundown, confirming that the model is consistent with FM-dye destaining when stimulation is 20 Hz.

Parameter values specified by the results from the original electrophysiological experiments - see ***Gabriel et al.*** (***2011***) - were the length of docked and undocked *tethering units* (4 vesicles, including the readily releasable vesicle when docked), the timing of recruitment of a vesicle from a docked tether unit to the release site when vacant (0.13 s^{-1} at rest, accelerating to 0.22 s^{-1} during 20 Hz stimulation - alpha in the Matlab code below), and the timing with which tethering units are replaced (0.017 s^{-1} at rest, accelerating to 0.025 s^{-1} during 20 Hz stimulation - gamma in Matlab code). However, the original results only specified parameters that are rate-limiting for neurotransmitter release during intense stimulation, and there were a variety of additional parameters - relevant to vesicle trafficking, but not rate-limiting for release - that were relevant to FM-dye destaining, especially during low frequency stimulation.

The most relevant additional parameters pertained to the release sites and included: (1) the number of types of release sites; (2) the probability with which each type catalyzes exocytosis after single action potentials (i.e., p_{rs} for ***p****robability of release* for the ***r****elease* ***s****ite* when occupied by a readily releasable vesicle, which is equivalent to $p_{v,hi}$ and $p_{v,lo}$ in ***Mahfooz et al., 2016***, except with the possibility for more than two types of release sites); and, (3) the relative amount of each type.

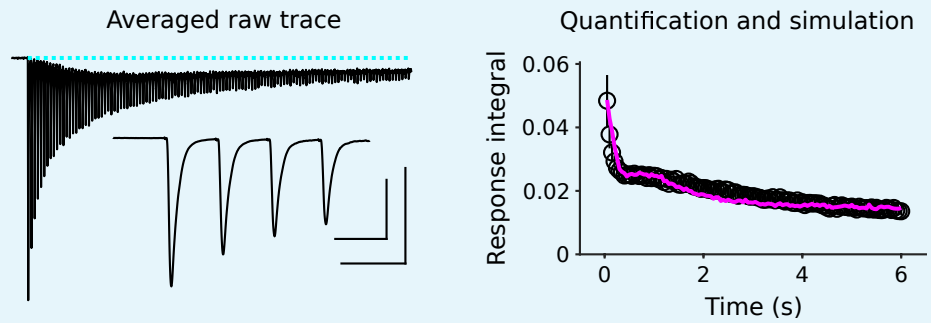
In addition, we fixed the number of non-docked tethering units that can exchange with each docked unit at 1, meaning that each release site would process vesicles from two tethering units (8 vesicles). The value was chosen because depletion of the readily releasable pool destained synapses by slightly more than 1/8 (0.15 ±0.01 in ***Figure 4***). This implies that a typical synapse with 7 release sites would contain 7 X 8 = 56 recycling vesicles, which is in-line with results in ***Ryan et al.*** (***1997***); ***Harata et al.*** (***2001***); ***Schikorski and Stevens*** (***2001***).

Next, for fitting destaining during 20 Hz stimulation, it was necessary to allow >5-fold facilitation, at least for the release sites with the lowest values for p_{rs}, because otherwise 20 Hz stimulation would not exhaust the readily releasable pool: exhaustion during 20 Hz stimulation is verified experimentally in Figure 2 of ***Garcia-Perez et al.*** (***2008***); and >5-fold facilitation is verified in Figure 2 of ***Stevens and Wesseling*** (***1999a***). We had facilitation increase with a single exponential with rate parameter of 30 action potentials to maintain consistency with Figure 2 of ***Stevens and Wesseling*** (***1999a***), but the precise timing was not

a key factor because of the flexibility provided by the three release site parameters.

Finally, we reasoned that previously docked tethering units would need to have the capacity to re-dock to the same release site. Otherwise: Either a large number of dye-stained vesicles would be trapped within synaptic terminals during long trains of low frequency stimulation; or quickly and slowly mobilized reserves would mix on the time course of minutes. A large number of trapped vesicles is ruled out in ***Figure 2A*** and elsewhere, and mixing is ruled out in ***Figure 3*** and ***Figure 8***, and elsewhere.

FM-dye destaining curves (***Appendix 1 Figure 1***) could be well fit by including as few as two types of release sites, but at least three types were required to match additionally the short-term depression seen in synaptic strength during 20 Hz stimulation (***Appendix 1 Figure 2***).



Appendix 1 Figure 2. Electrophysiological recordings of synaptic responses between pairs of neurons in culture during 6 s of 20 Hz stimulation, and corresponding simulation using the model in ***Appendix 1 Figure 1*** (magenta line) The electrophysiological trace is the average across 11 pairs, including the pairs that constituted the untreated wildtype control in Figure 5 of ***García-Pérez et al.*** (***2015***). The inset shows the first 4 responses on an expanded time scale. Outer scale bars pertain to the entire trace and are 500 pA by 1 s; inner bars pertain to the inset and are 500 pA by 50 ms. Responses were quantified by integrating each 50 ms interval after subtracting the baseline before the first response (dashed cyan line), so that later responses included a substantial component caused by asynchronous release (***Hagler and Goda, 2001***). Results for each cell pair were normalized by the sum of the first 40 responses (2 s) before combining across cell pairs; we normalized this way because of extreme variation between cell pairs in the short-term plasticity seen during the first few responses - the paired pulse ratio of the first two responses varied from 1.27 to 0.64 - and because 40 responses has been used elsewhere to approximate readily-releasable pool size (***Murthy and Stevens, 1999***); the 80 responses to trains designed to ensure exhaustion above would be an overestimate because of ongoing recruitment to vacant release sites (***Wesseling and Lo, 2002***).

The Matlab code for simulating the model for a single release site was:

```
function [DestainTimeCourse, SynapticStrengthTimeCourse] = ...
DestainReleaseSite(NumberOfTetherUnits, Time_seconds, NumberVesiclesPerUnit, ...
                   prs_VsTime, alpha_VsTime, gamma_VsTime, ...
                   ActionPotentials_VsTime)
   DestainTimeCourse(length(Time_seconds)) = nan;
   SynapticStrengthTimeCourse(length(Time_seconds)) = 0;
   TetherUnits(1:NumberOfTetherUnits, 1:NumberVesiclesPerUnit) = 1;
          %All vesicles in all tether units are stained to start with
          %Each space on tether unit can be 1 (full, stained) -1(full, unstained)
          %or 0 (vacant)
   DeltaTime_seconds = Time_seconds(2)-Time_seconds(1);
   DockedUnit = 1;
   for i = 1:length(Time_seconds)
       DestainTimeCourse(i) = sum(TetherUnits(:)==1);
            %fluorescence is equivalent to number of stained vesicles
```

```
        if (TransitionP(gamma_VsTime(i), DeltaTime_seconds))
            [DockedUnit, TetherUnits] = ...
                 SwitchDockedUnit(DockedUnit, 1:NumberOfTetherUnits, TetherUnits);
        end
        if (TetherUnits(DockedUnit,end)==0)
            if (TransitionP(alpha_VsTime(i),DeltaTime_seconds))
                TetherUnits = AdvanceTetherUnit(DockedUnit, TetherUnits);
            end
        end
        if (ActionPotentials_VsTime(i) && ...
            (TetherUnits(DockedUnit,end)~=0) && ...
            (prs_VsTime(i)) > rand())
                 TetherUnits(DockedUnit,end) = 0;
                 SynapticStrengthTimeCourse(i) = 1;
         end
    end

function P = TransitionP(DeltaTime_seconds, rateconstant)
    P = ((1-exp(-rateconstant*DeltaTime_seconds)) > rand());

function [NewDocked, TetherUnits] = ...
               SwitchDockedUnit(CurrentlyDocked, AllChoices, TetherUnits)
   AllChoices(AllChoices==CurrentlyDocked) = [];
   NewDocked = randsample(AllChoices, 1);
   TetherUnits(NewDocked, TetherUnits(NewDocked, :)==0) = -1;
   % The preceding line replaces vacant spaces on tethers with unstained vesicles

function TetherUnits = AdvanceTetherUnit(DockedUnit, TetherUnits)
    if (TetherUnits(DockedUnit,end) ~= 0) %Only advance if vacant (error check)
        warning('Trying to advance a chain with no vacancy at end');
    else
        for i = length(TetherUnits(DockedUnit,:)):-1:2
            TetherUnits(DockedUnit, i) = TetherUnits(DockedUnit,i-1);
        end
        TetherUnits(DockedUnit, 1) = 0;  %This makes the end vacant
    end
```

Simulations were repeated 1000 times for each type of release site for ***Appendix 1 Figure 1*** and 100 000 times for ***Appendix 1 Figure 2*** before averaging and then calculating the weighted sum across types of release sites.

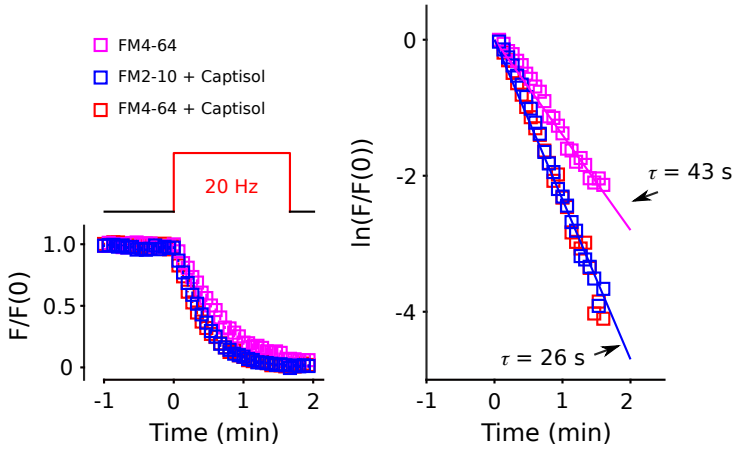


Figure 2–Figure supplement 1. Synapses were stained with 60 s of 20 Hz electrical stimulation in the presence of FM4-64 or FM2-10, washed, and then destained with 100 s of 20 Hz stimulation in the presence or absence of Captisol as diagrammed above plot to the left. The plot to the right is the semi-log plot of the same destaining time course. This experiment shows that Captisol accelerated destaining of FM4-64, but no additional acceleration was seen when the dye was FM2-10, which dissociates from membranes 30-fold faster. The result indicates that FM4-64 is cleared completely from vesicular membrane after a single round of exocytosis in the presence of Captisol.

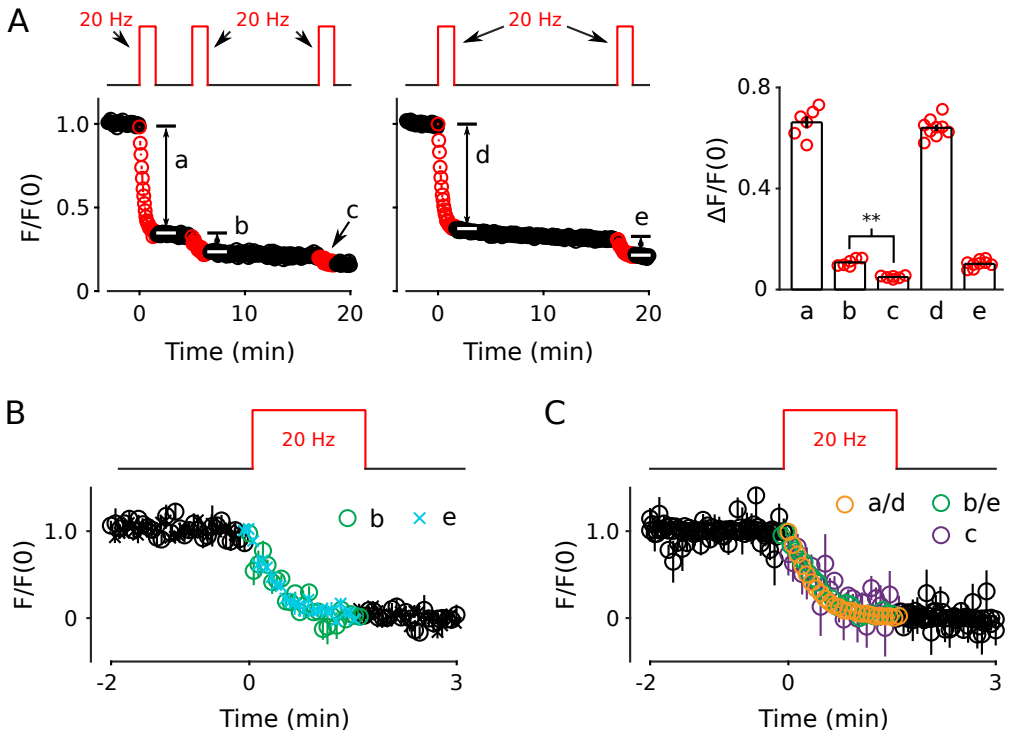


Figure 2–Figure supplement 2. Analysis of FM4-64 signal remaining after 20 Hz stimulation for 100 s. **(A)** Unlike elsewhere throughout this report, the remaining signal was not subtracted before normalization; the value of zero indicates the background signal from non-neuronal areas of the cell culture that did not destain during electrical stimulation. The plots show that 100 s of 20 Hz stimulation likely does not completely destain all recycling vesicles because a small amount of additional destaining could be induced with additional 20 Hz stimulation (**b** and **e**). The amount was similar when the additional stimulation was initiated after 3.3 min or after 15.3 min of rest (bar graph). And, destaining during a third train (**c**) was even less (** signifies $p < 0.01$, rank sum). **(B)** Overlay of destaining time course of second 20 Hz trains begun either 3.3 min after the first train (i.e., **b**), or 15.3 min after (**e**). Unlike for **Panel A** the remaining signal was subtracted, and both time courses were re-normalized so that the baseline was 1.0. The plot shows that the two were similar, indicating that 12 min of additional rest did not alter the time course of destaining. **(C)** Overlay of destaining time courses during the first, second and third 20 Hz trains showing that the time course was essentially the same under all conditions.

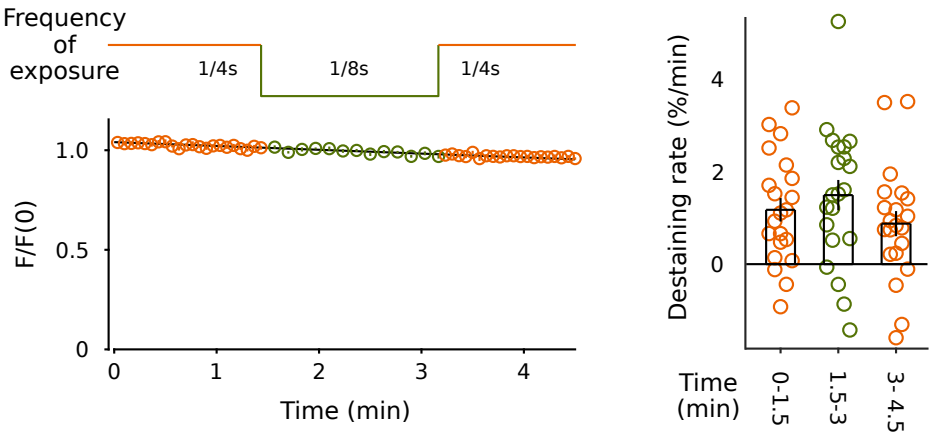
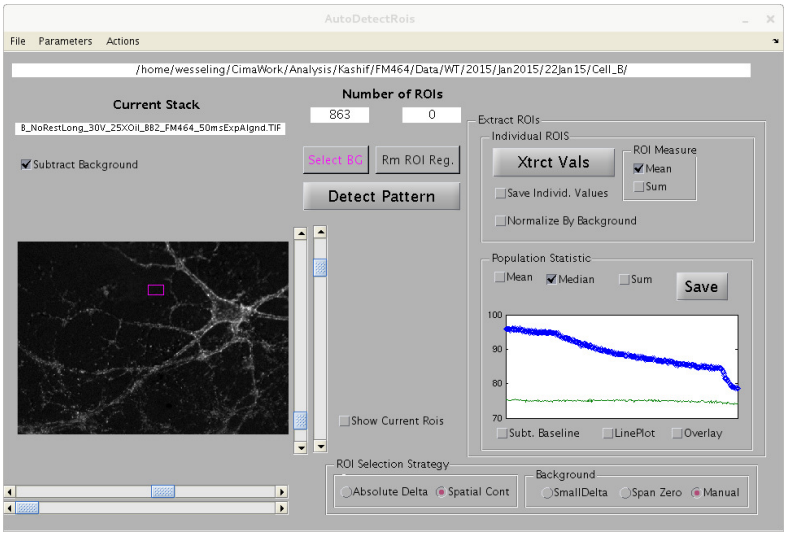


Figure 2–Figure supplement 3. No evidence for photobleaching. Baseline destaining did not decrease when exposure to light was decreased to half by decreasing the acquisition rate from 1/4 to 1/8 s ($n = 21$ preparations).

A



B

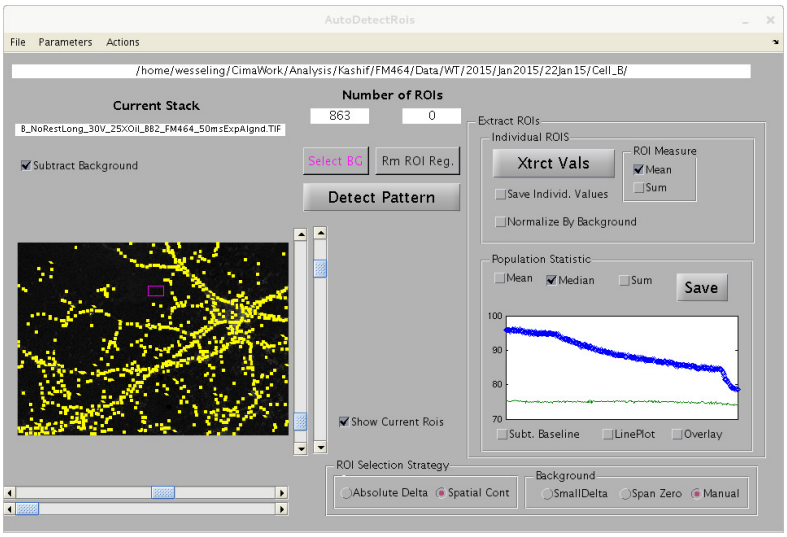


Figure 2–Figure supplement 4. Graphical user interface for semi-automatic ROI detection. A value for contrast for each 2X2 pixel region of each image was calculated by subtracting the mean value of surrounding pixels from the mean value of the pixels within the region. Regions were then sorted by the change in contrast during the experiment, and regions overlapping with regions with larger change in contrast were eliminated. A threshold for the minimum change in contrast for consideration as a region of interest (ROI) was then set subjectively using the upper horizontal scroll bar beneath the image within the graphical user interface. The image is the difference calculated by subtracting the mean of destained images from the mean of images before destaining. The software has the capability of selecting background regions automatically, but, for the present study, a background region was selected by hand (magenta box). The blue circles in the plot in the "Population Statistic" box are the median ROI values vs time, and the green line is background. **(A)** Without displaying locations of ROIs. **(B)** ROIs are demarcated by yellow boxes.

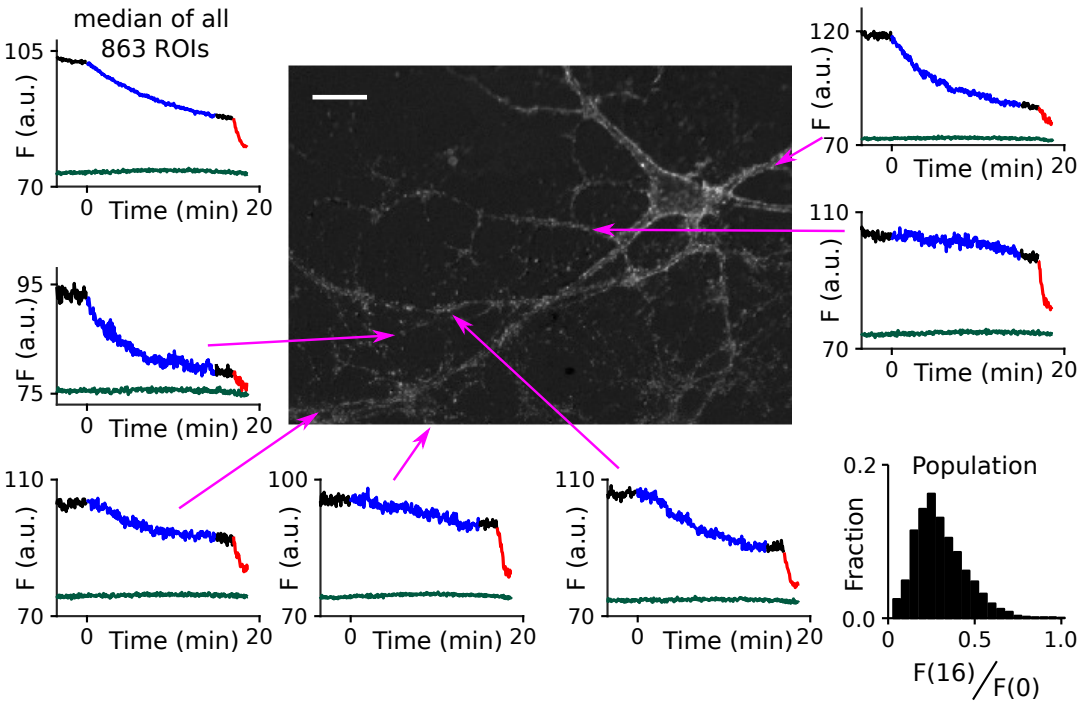


Figure 2–Figure supplement 5. Extensive heterogeneity among synapses. Time courses are FM4-64 destaining at individual ROIs indicated in the central image during 15 min of 1 Hz stimulation (blue portions of traces) followed by 100 s at 20 Hz (red); the lower trace in each plot (green/blue) is background measured at a nearby area. The amount of destaining during 1 Hz stimulation could be quantified, with a single parameter, by dividing the signal remaining during the interval after 1 Hz stimulation and before 20 Hz - i.e., $F(16)$ - by the signal before 1 Hz stimulation - i.e., $F(0)$. The heterogeneity among synapses could then be summarized with the histogram in the lower right. The scale bar in the central image is 20 μm.

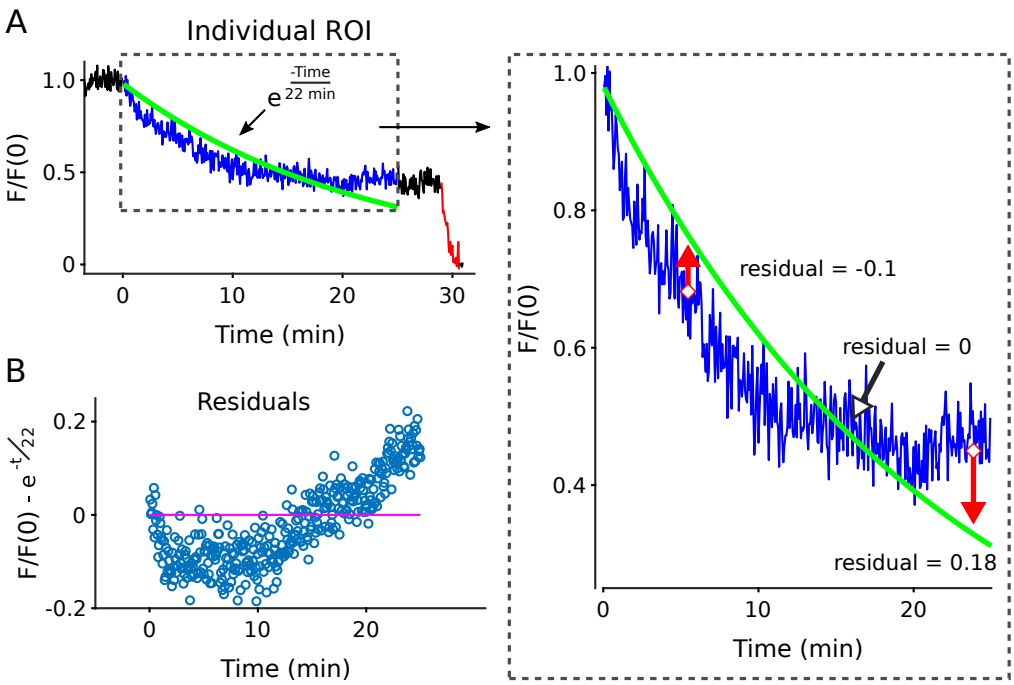


Figure 2–Figure supplement 6. Illustration of procedure for calculating residuals after fitting with a single exponential. **(A)** Blue traces are destaining time courses during 25 min of 1 Hz stimulation, green lines are the best fitting single exponentials (i.e., Eqn 2; see **Methods and Materials** for fitting procedure). The best fitting single exponentials appear to come close to the destaining time courses in linear plots, but this is illusory, unrelated to mathematical adequacy. The absence of a good fit is more evident when replotted on semi-log plots (***Figure 2–Figure Supplement 7B***), or in the large changes over time observed in the fractional destaining measurement used to quantify deviations from Eqn 1 throughout the manuscript. **(B)** The residual values are calculated by subtracting the best fitting instantiation of Eqn 2 from the destaining time courses. A mathematically adequate fit would imply that residual values are scattered at random about zero (magenta line), but this almost never occurred. For a statistical test of the adequacy of each fit, we compared the residual values during the first 12.5 min of 1 Hz stimulation to the values during minutes 12.5 - 25 using the Wilcoxon rank sum method. Rejection of adequacy of fit was statistically significant for >90 % of individual ROIs, and typically highly significant for ROIs where signal/noise was good; the statistical significance for the individual analyzed here was $p < E - 47$.

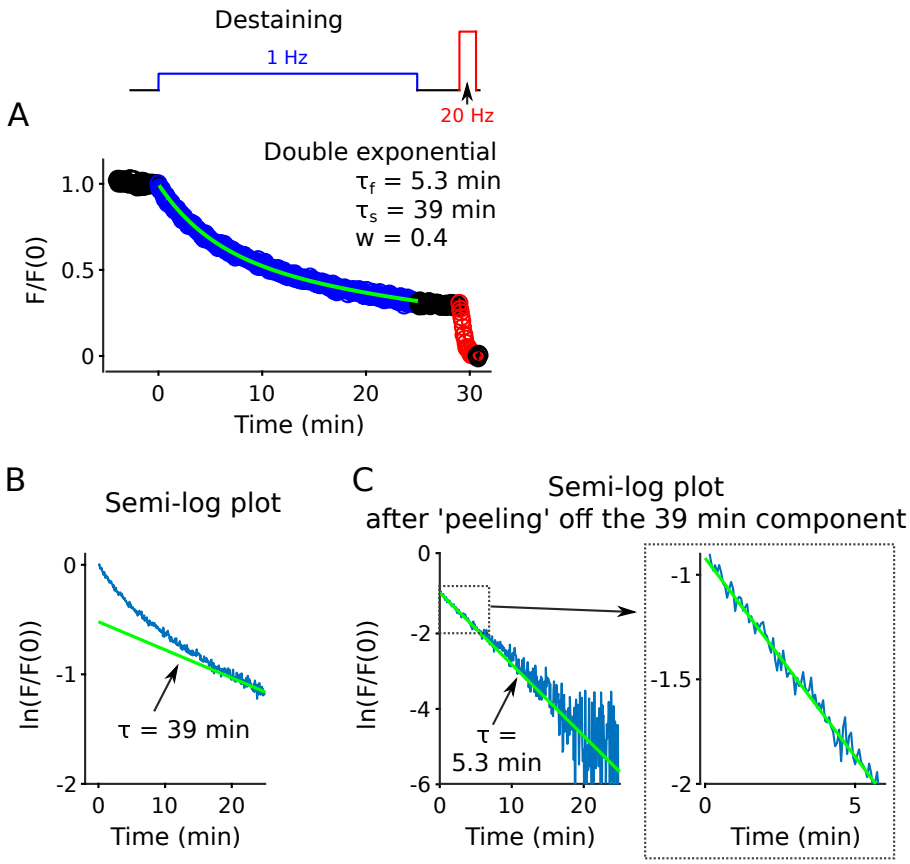


Figure 2–Figure supplement 7. Best fitting double exponential during destaining driven by 25 min of 1 Hz stimulation. The function was: $F(t) = F(0) \cdot [w \cdot e^{\frac{-t}{\tau_f}} + (1-w) \cdot e^{\frac{-t}{\tau_s}}]$ with τ_f, τ_s and w as indicated at top. **(A)** Linear plot. **(B)** Semi-log plot with single exponential $F(t) = F(0) \cdot [(1-w) \cdot e^{\frac{-t}{\tau_s}}]$. **(C)** Exponential peeling: semi-log plot after subtracting the single exponential in **Panel B**.

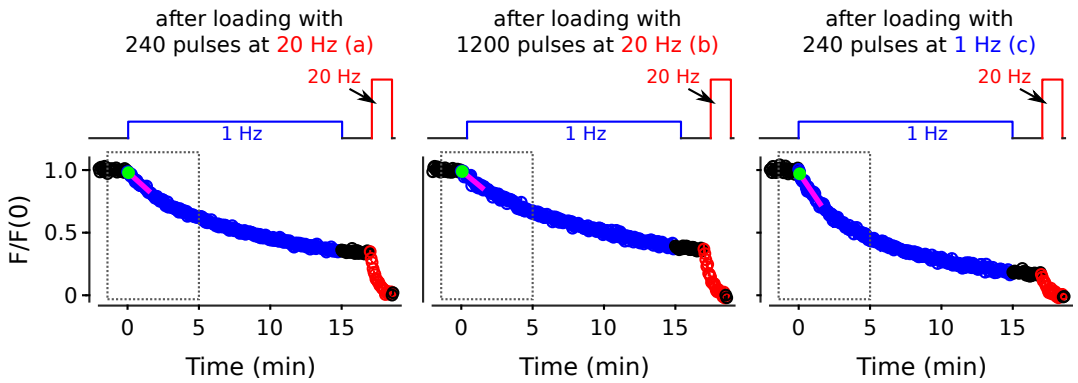


Figure 7–Figure supplement 1. Full destaining time courses for experiments in **Figure 7**. Values within gray dashed boxes are already plotted in **Figure 7*B***. The letters **a**, **b**, and **c** correspond to the same letters in **Figure 7*A-B***.

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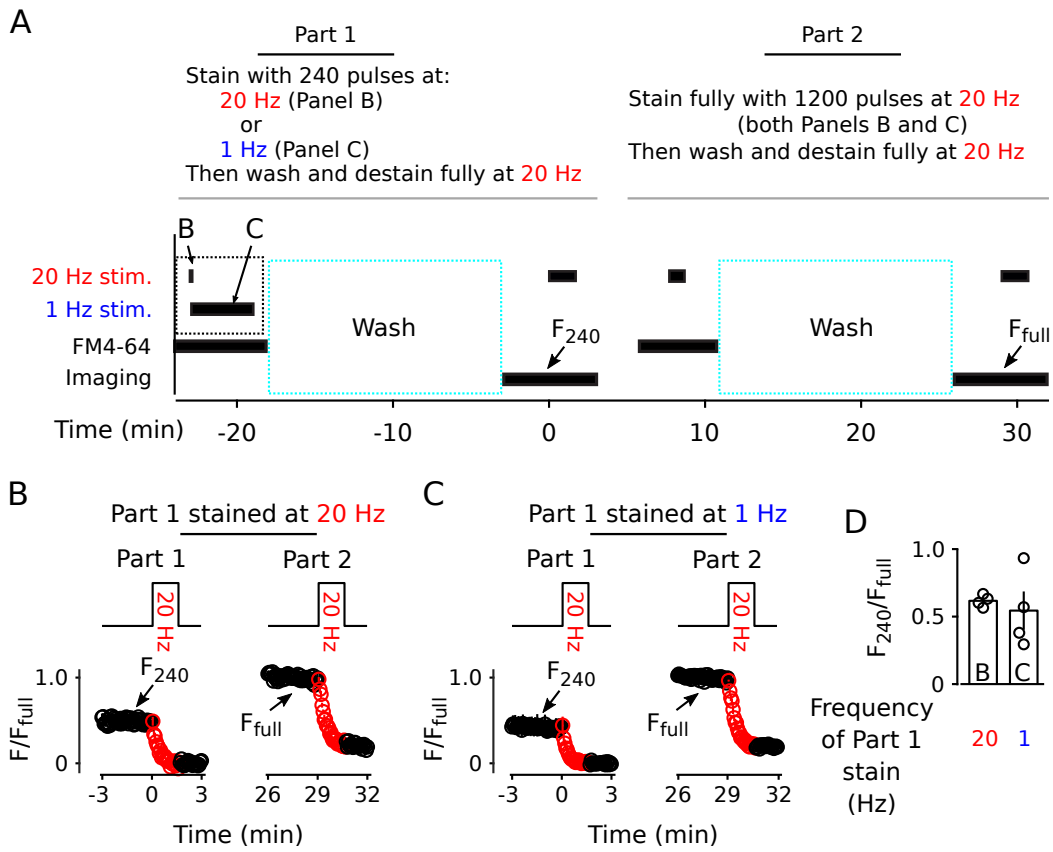

Figure 7–Figure supplement 2. Similar amount of staining induced by 240 pulses at 1 vs 20 Hz. **(A)** Experimental protocol. **(B)** Destaining (2000 pulses at 20 Hz) after staining with 240 pulses at 20 Hz (Part 1) and, subsequently, after staining with 1200 pulses at 20 Hz (Part 2); (n = 4). **(C)** Same as **Panel B** except stimulation frequency during staining in Part 1 was 1 instead of 20 Hz (n = 4). **(D)** Quantification of fractional staining induced by 240 pulses in **Panels B & C**.

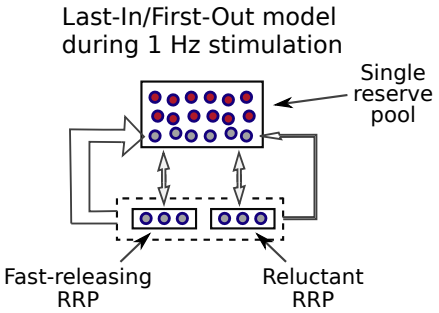

Figure 8–Figure supplement 1. Last-in/first-out models are a special case of serial models where reserve vesicles that have been reconstituted from recycled membrane are recruited to the readily releasable pool before vesicles that have been in the reserve pool for longer. If so, a small number of reserve vesicles might undergo multiple rounds of exocytosis during long-trains of low frequency stimulation, whereas others would not undergo exocytosis a single time. This could explain the decrease in fractional destaining seen in FM-dye destaining experiments during 1 Hz stimulation (e.g., **Figure 2*B-C***), and other observations. However, without a mixing mechanism, the vesicles that did not undergo exocytosis during 1 Hz stimulation would be recruited to the readily releasable pool with a delay during 20 Hz stimulation, which is not compatible with the results in **Figure 9*B-C***. And, mixing is ruled out in the analysis of results in **Figure 10**.

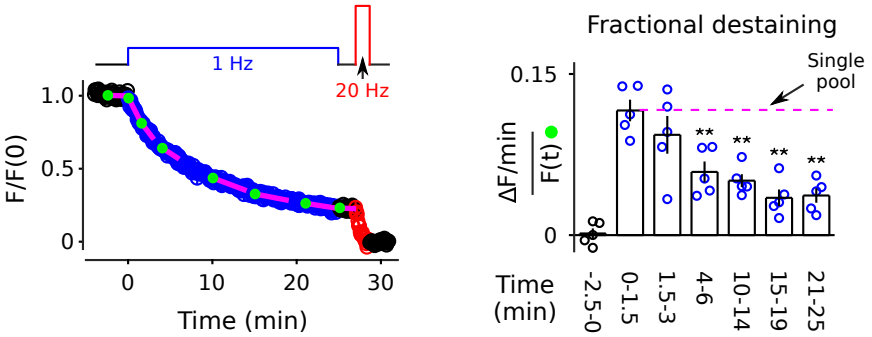

Figure 8–Figure supplement 2. FM4-64 destaining at 35 C. Analogous to **Figure 2*B-C***, except at 35 C.

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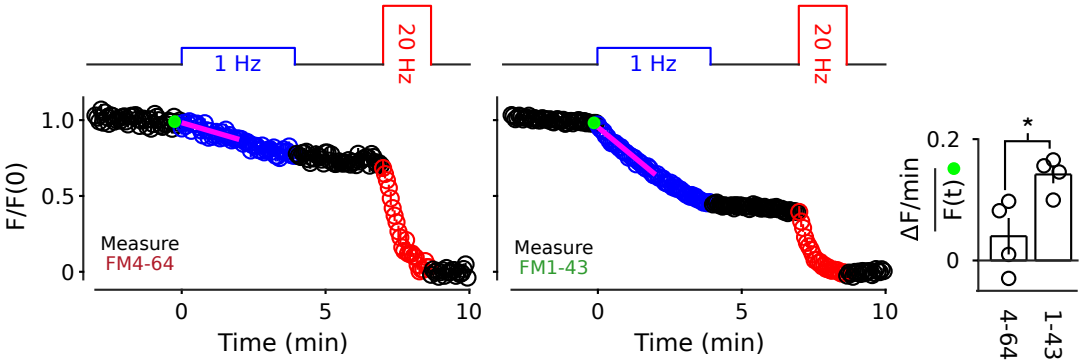

Figure 8–Figure supplement 3. Two color experiment at 35 C. Analogous to **Figure 8*A***, except at 35 C

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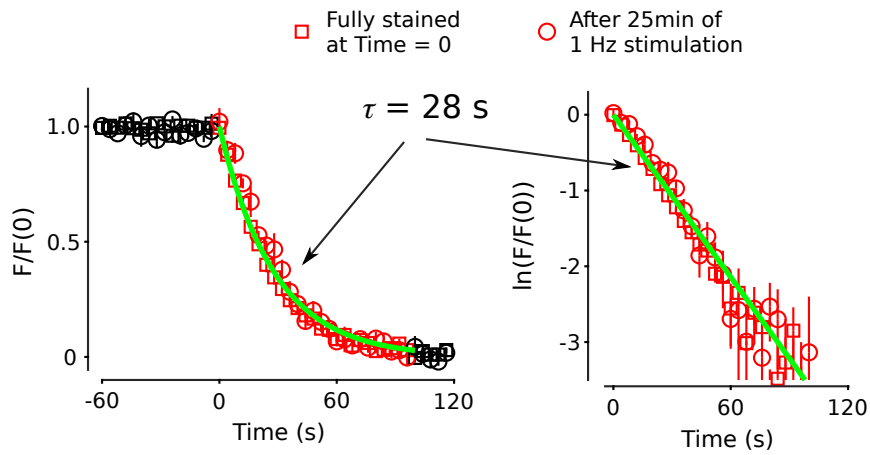

Figure 9–Figure supplement 1. Linear and semi-log plots of overlaid destaining time courses during 20 Hz stimulation at synapses that were initially fully stained (squares) and at synapses that were partially destained beforehand by 25 min of 1 Hz stimulation (circles). Data are the same as in **Figure 9** except the time courses from partially destained synapses in **Figure 9*B*** were re-normalized by the value of $F(t)$ during the rest interval between the 1 Hz and 20 Hz stimulation. Green lines are the single exponential described by Eqn 2 with $k = \frac{1}{\tau} = \frac{1}{28\,s}$. The observation that the time courses are fit by a straight line on a semi-log plot confirms that destaining follows a single exponential, which is mathematically equivalent to the observation in **Figure 9*C*** that fractional destaining does not change over the time courses.

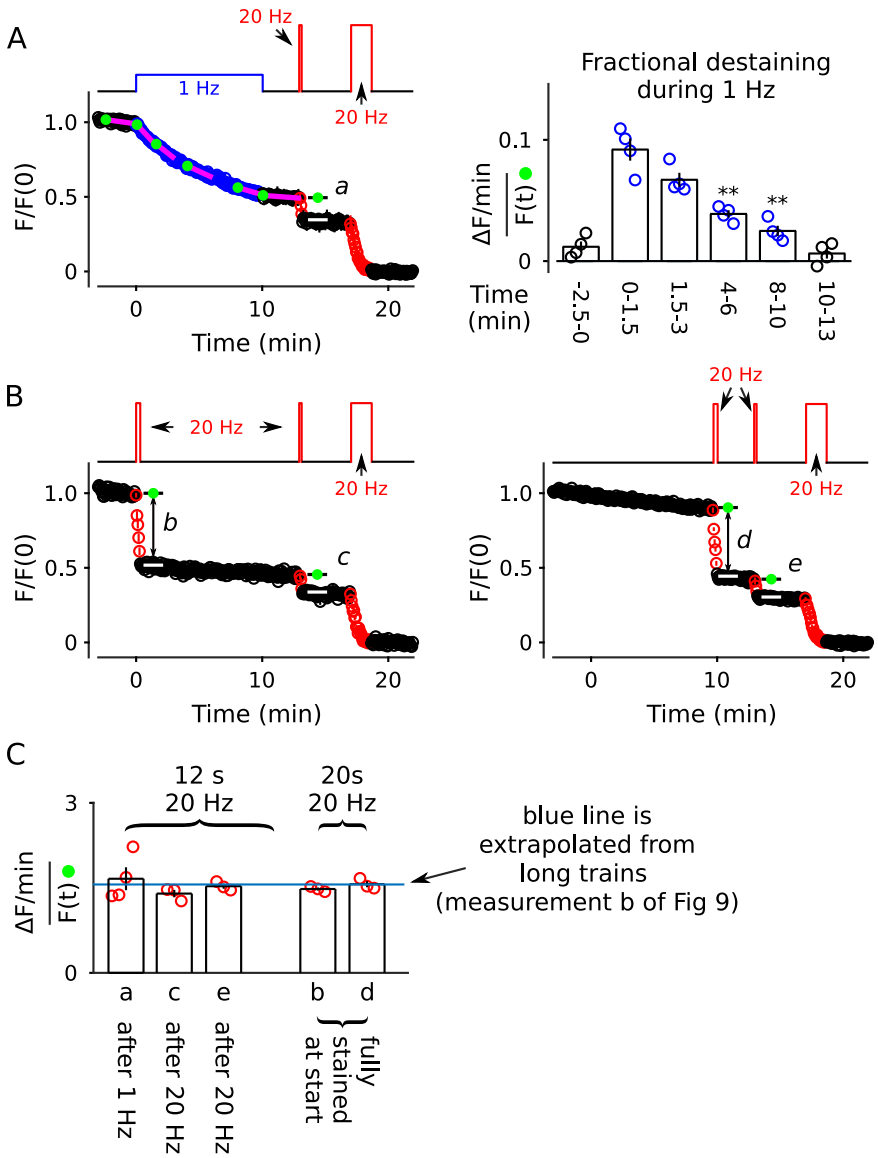

Figure 9–Figure supplement 2. Further evidence that the decrease in fractional destaining during 1 Hz stimulation is no longer evident when subsequent stimulation is 20 Hz. For all experiments, synapses were first stained with FM4-64 with the standard stimulation protocol of 20 Hz stimulation for 60 s. **(A)** Destaining during 10 min of 1 Hz stimulation followed by 12 s at 20 Hz and then 100 s at 20 Hz ($n = 4$). The bar graph confirms that 10 min of 1 Hz stimulation drives fractional destaining to a low rate when measured during continued 1 Hz stimulation (** signifies $p < 0.01$, rank sum). The calculation of fractional destaining is analogous to **Figure 2**C. **(B)** Similar to destaining in **Panel A**, except the first train was 20 s at 20 Hz instead of 10 min at 1 Hz; 20 s at 20 Hz was chosen because it destains the synapses to the same level as 10 min at 1 Hz ($n = 3$ for both types of experiments). **(C)** Quantification of fractional destaining: during 12 s of 20 Hz stimulation after partial destaining with 1 Hz or 20 Hz stimulation from **Panels A-B** (a, c, e); and during 20 s of 20 Hz stimulation at fully stained synapses from **Panel B** (bars b, d). The blue line is the mean fractional destaining during the 1st 20 s of 20 Hz stimulation during long trains (b in **Figure 9*A***); the match to fractional destaining during short trains confirms that FM4-64 is cleared from membranes quickly compared to the overall timing of exocytosis during 20 Hz stimulation (i.e., in the presence of Advasep-7/Captisol used throughout the present study).

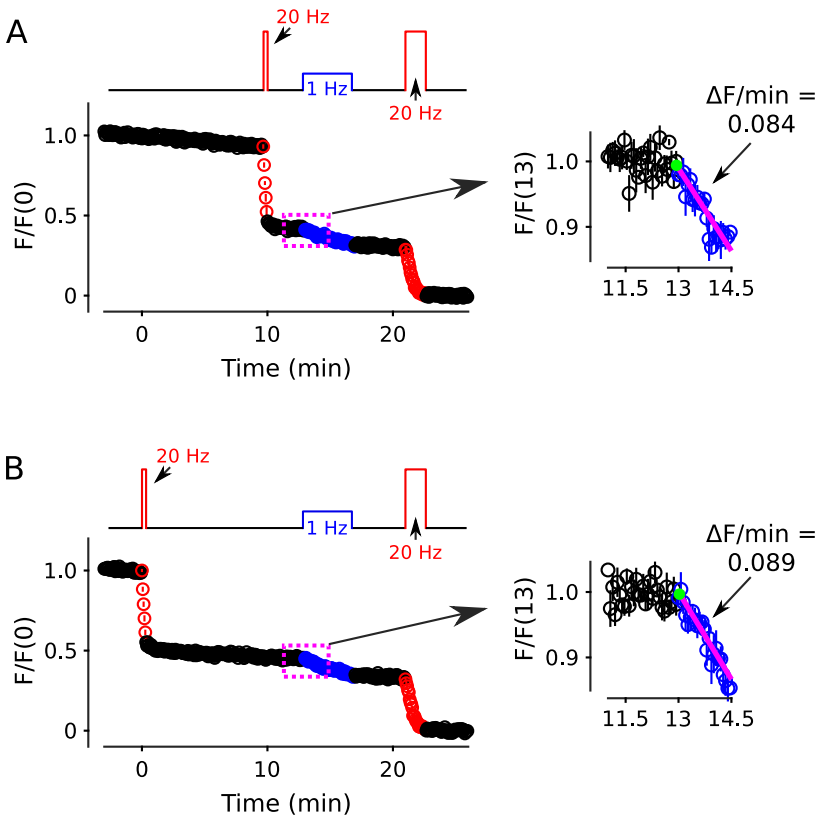

Figure 10–Figure supplement 1. Control showing destaining during a 1 Hz train following a 20 Hz train is equivalent after delays of 0 and 10 min. The control is relevant to **Figure 10*A-C*** where the goal was to compare destaining during 1 Hz trains following a 10 min-long 1 Hz train to following a 20 s-long 20 Hz train. When designing the experiment, it was not clear if the 20 Hz train (i.e., in **Figure 10*B***) should be matched in time to the beginning or to the end of the 10 min-long 1 Hz train (in **Figure 10*A***). Therefore, both types of experiments were conducted and were interleaved with each other and with the experiments documented in **Figure 10*A***. **(A)** After a delay of 10 min ($n = 6$). **(B)** After no delay; the full time course is replotted from **Figure 10*B***, but the inset here pertains only to the 8 experiments summarized by the full time course whereas the inset of **Figure 10*B*** pertains to all 14 experiments summarized here and in **Panel A**.

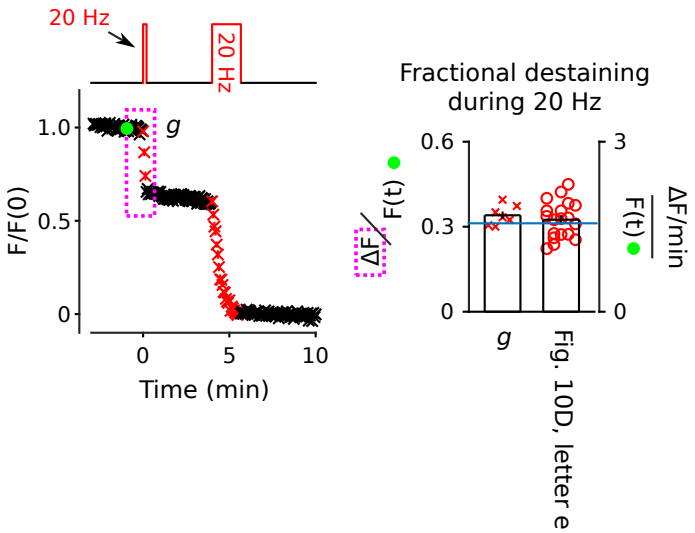

Figure 10–Figure supplement 2. Fully stained synapses were destained with 12 s of 20 Hz stimulation, followed by complete destaining with 100 s of 20 Hz stimulation ($n = 7$). The bar graph shows that fractional destaining during the 12 s-long train matches fractional destaining during 12 s of 20 Hz stimulation initiated after 10 min of 1 Hz stimulation in **Figure 10*D*** (magenta box e). The blue line in the bar graph is the mean fractional destaining during the 1st 20 s of 20 Hz stimulation during long trains (b in **Figure 9*A***), and is included here to facilitate comparison to ***Figure 9–Figure Supplement 2***.