The homeodomain transcriptional regulator DVE-1 directs a program for synapse elimination during circuit remodeling

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Contributions Summary

KDA generated strains, transgenic lines, molecular constructs, confocal microscopy images and analysis, performed optogenetic behavioral experiments, photoconversion experiments, modencode ChIP-seq analysis and pathway analysis. SR performed all calcium imaging experiments/analysis and conducted single worm tracking. KB performed all Bortezomib inhibitor experiments and analysis. CL generated most vectors and constructs. JR assisted with generation of CRISPR/Cas9 generated strains. WA and MR assisted with aldicarb behavioral assay. DO assisted with EMS screen and isolation of *dve-1* mutant. CB and MD aided in CloudMap bioinformatic analysis of the *uf171* mutant. MMF and KDA designed and interpreted results of all experiments and wrote the manuscript.

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Abstract

An important step in brain development is the remodeling of juvenile neural circuits to establish mature connectivity. The elimination of juvenile synapses is a critical step in this process; however, the molecular mechanisms directing synapse elimination activities and their timing are not fully understood. We identify here a conserved transcriptional regulator, DVE-1, that shares homology with mammalian special AT-rich sequence-binding (SATB) family members and directs the elimination of juvenile synaptic inputs onto remodeling *C. elegans* GABAergic neurons. Dorsally localized juvenile acetylcholine receptor clusters and apposing presynaptic sites are eliminated during maturation of wild type GABAergic neurons but persist into adulthood in *dve-1* mutants. The persistence of juvenile synapses in *dve-1* mutants does not impede synaptic growth during GABAergic remodeling and therefore produces heightened motor connectivity and a turning bias during movement. DVE-1 is localized to GABAergic nuclei prior to and during remodeling and DVE-1 nuclear localization is required for synapse elimination to proceed, consistent with DVE-1's function as a transcriptional regulator. Pathway analysis of DVE-1 targets and proteasome inhibitor experiments implicate transcriptional control of the ubiquitin-proteasome system in synapse elimination. Together, our findings demonstrate a new role for a SATB family member in the control of synapse elimination during circuit remodeling through transcriptional regulation of ubiquitin-proteasome signaling.

Introduction

The mature human brain is composed of billions of neurons that are organized into functional circuits based on stereotyped patterns of synaptic connections that optimize circuit performance. Mature circuit connectivity is choreographed through a remarkable period of developmental circuit rewiring that is broadly conserved across species [1-4]. During this rewiring or remodeling phase, the mature circuitry is established through a tightly controlled balance: on the one hand, degenerative processes promote the elimination of juvenile synapses, while, on the other hand, maintenance or growth processes support the stabilization or formation of new connections. A combination of cell-intrinsic and extrinsic factors shape the progression of these events. For instance, activity-dependent microglial engulfment and elimination of synaptic material shapes connectivity of the retinogeniculate system in mice [5-8], while cell-intrinsic genetic programs such as the circadian clock genes Clock or Bmal1 influence GABAergic maturation and plasticity-related changes in the neocortex [9]. While molecular mechanisms supporting axon guidance and synapse formation have received considerable attention, our understanding of neuron-intrinsic molecular mechanisms controlling synapse elimination remains more limited. In particular, it is unclear how neuron-intrinsic synapse elimination processes are engaged in developing neural circuits. Improved mechanistic knowledge of these processes offers potential for important advances in our grasp of brain development. This knowledge may also inform the pathology underlying numerous neurodevelopmental diseases associated with altered connectivity and neurodegenerative diseases where synapse loss is a hallmark feature [10-13]. Indeed, recent work has suggested intriguing parallels between the elimination of synapses during development and neurodegenerative processes during disease [10-13].

The nematode *Caenorhabditis elegans* offers significant assets for addressing mechanistic questions about developmental neural circuit remodeling, particularly synapse elimination. *C. elegans* progresses through a highly stereotyped period of nervous system remodeling that establishes the neural connections characteristic of mature animals. 80 of the 302 neurons composing the adult nervous system, including 52 motor neurons, are born post-embryonically and integrated into pre-existing juvenile circuits following the first larval (L1) stage of development [14, 15]. The incorporation of these post-embryonic born motor neurons is accomplished following the first larval stage (L1) of development through a remarkable reorganization of circuit connectivity. One of the most striking aspects of this reorganization is the remodeling of synaptic connections in the GABAergic dorsal D-class (DD) motor neurons (**Figure 1A**) [16, 17]. Immediately after hatch, juvenile cholinergic synaptic inputs onto GABAergic DD neurons are located dorsally, while juvenile DD synaptic outputs onto muscles are located ventrally. During remodeling, the juvenile dorsal cholinergic synaptic inputs onto DD neurons are eliminated, and new synaptic inputs from post-embryonic-born presynaptic cholinergic neurons are established ventrally. In parallel, ventral DD GABAergic synaptic terminals are relocated dorsally, forming new GABAergic synaptic contacts onto dorsal muscles [18-22]. Though we now have a growing appreciation of the cellular processes that direct the post-embryonic redistribution of DD GABAergic outputs onto dorsal muscles, we have a limited understanding of how cholinergic inputs to DD neurons are remodeled. Prior work suggested a mechanism for antagonizing the remodeling of cholinergic inputs onto DD neurons through temporally controlled expression of the Ig domain family member OIG-1 [23, 24]; however, the mechanisms that promote remodeling of these inputs, in particular their elimination, have remained uncharacterized.

We report the identification of a mechanism for neuron-intrinsic transcriptional control of synapse elimination during remodeling of the *C. elegans* motor circuit. From a forward genetic screen to isolate mutants whose juvenile postsynaptic sites on GABAergic DD neurons persist in mature

105 animals, we obtained a mutation in the homeodomain transcriptional regulator *dve-1* that shares
106 homology with mammalian special AT-rich sequence-binding (SATB) family members. We show
107 that DVE-1 acts cell autonomously in GABAergic DD neurons to promote the removal of juvenile
108 cholinergic synaptic inputs. Juvenile synaptic inputs are maintained into adulthood in *dve-1*
109 mutants, leading to an accumulation of presynaptic cholinergic vesicles as well as alterations in
110 circuit function and movement. We further show that precocious synapse elimination in *oig-1*
111 mutants is reversed by mutation of *dve-1*, suggesting that DVE-1 promotes pro-degenerative
112 processes that are antagonized by OIG-1. Our results reveal a novel neuron-intrinsic mechanism
113 for developmentally timed synapse elimination through converging pro-degenerative and
114 maintenance pathways.

115

Results

Distinct mechanisms direct developmental remodeling of presynaptic terminals versus postsynaptic sites in GABAergic neurons

Previous work by our lab and others showed that clusters of postsynaptic ionotropic acetylcholine receptors (iAChR) denote postsynaptic sites on DD neurons and undergo dorsoventral remodeling during the transition between the 1st and 2nd larval stages of development (L1/L2 transition) [23-25]. During this period, dorsal postsynaptic sites on DD neurons are removed, and the growth of new ventral postsynaptic sites is indicated by the appearance of newly formed ventral iAChR clusters. In animals co-expressing the synaptic vesicle marker mCherry::RAB-3 and the iAChR marker ACR-12::GFP, we found that the remodeling of cholinergic postsynaptic sites and GABAergic presynaptic terminals in DD neurons occurred with similar time courses, consistent with prior work (**Figure S1.1A,B**). Surprisingly, however, we found that mutations in several genes previously implicated in the remodeling of GABAergic presynaptic terminals had no appreciable effect on the remodeling of cholinergic postsynaptic sites in DD neurons (**Figure S1.1C, Table 1**). For example, juvenile mCherry::RAB-3 clusters were not fully removed from the ventral nerve cord of *ced-3/*caspase mutants at the L4 stage [26], indicating a failure to properly relocate GABAergic presynaptic terminals during remodeling. However, juvenile cholinergic postsynaptic sites were properly removed in DD neurons of *ced-3* mutants, as indicated by the absence of iAChR clusters in the dorsal nerve cord after the L2 stage (**Figure S1.1C**). Indeed, lingering synaptic vesicle clusters in the ventral nerve cord of *ced-3* mutants were interleaved with newly formed ventral iAChR clusters, demonstrating that the formation of new ventral postsynaptic sites during remodeling also occurs independently of *ced-3*. Mutations in several genes important for neurotransmitter release and calcium signaling also did not appreciably alter the remodeling of postsynaptic sites in DD neurons, though we noted clear delays in the remodeling of DD presynaptic terminals as found previously [19, 21] (**Table 2**). Of the genes we

141 tested, only mutation of the RyR/*unc-68* gene produced a modest delay in the remodeling of
142 postsynaptic sites, suggesting calcium release from intracellular stores contributes (**Table 2**).
143 Taken together, our findings demonstrate that mechanisms for remodeling postsynaptic sites in
144 DD neurons are distinct from those previously implicated in the remodeling of DD GABAergic
145 presynaptic terminals.

146

147 **Identification of *dve-1* as a novel transcriptional regulator of synapse elimination**

148 Motivated by these findings, we pursued a forward mutagenesis screen to identify novel
149 mechanisms controlling the remodeling of postsynaptic sites in DD neurons. Specifically, we
150 screened to obtain mutants where juvenile postsynaptic sites, indicated by dorsal iAChR clusters,
151 were not properly eliminated during remodeling and instead persisted into maturity (**Figure**
152 **S1.2A,B**), and isolated a recessive mutant, *uf171*. Dorsal postsynaptic sites are normally
153 eliminated before the L2 stage (22 hours after hatch) in wild type but remained visible through the
154 late L4 stage (>40 hours after hatch) in *uf171* mutants (**Figure 1B,C,E; Figure S1.3A**). Whole
155 genome sequence analysis of *uf171* mutants revealed a point mutation in the gene encoding the
156 homeodomain protein DVE-1, producing a proline to serine (P/S) substitution (**Figure 1D**).
157 Expression of the wild type *dve-1* gene in *dve-1(uf171)* mutants restored normal elimination of
158 juvenile postsynaptic sites (**Figure 1B,C; Figure S1.3A),** while *dve-1* overexpression in wild type
159 animals did not produce appreciable changes in removal (**Figure 1B,C; Figure S1.3A**). A similar
160 failure in the elimination of juvenile postsynaptic sites was also evident in another available *dve-*
161 *1* mutant, *dve-1(tm4803)*, that harbors a small insertion/deletion mutation (**Figure 1B,C; Figure**
162 **S1.3A**). DVE-1 was of particular interest as it is a homeodomain transcription factor sharing
163 homology with mammalian SATB transcription factors and was previously implicated in the
164 regulation of a mitochondrial stress response in *C. elegans* [27]. The P/S substitution encoded by

165 *dve-1(uf171)* affects a highly conserved proline residue predicted to lie within a loop between
166 helices I and II of the first homeobox domain of *dve-1*. *dve-1(tm4803)* deletes a portion of
167 predicted helix III in the same homeobox domain and a splice site leading to 65 bp insertion
168 (**Figure 1D**) [28]. As *dve-1* null mutants are embryonic lethal [27], both mutations are predicted
169 to be hypomorphic.

170 The postsynaptic scaffold protein LEV-10 is associated with cholinergic postsynaptic sites in body
171 wall muscles and GABAergic neurons [29, 30]. Using a previously developed strategy for cell-
172 specific labeling of endogenous LEV-10 [30], we found that mutation of *dve-1* also slowed the
173 removal of LEV-10 from the dorsal processes of DD neurons during remodeling. LEV-10 was
174 primarily associated with dorsal processes prior to remodeling and was redistributed to ventral
175 processes during remodeling (**Figure 1F**). Similar to juvenile iAChR clusters, dorsal LEV-10
176 scaffolds in GABAergic neurons of *dve-1* mutants were not properly eliminated during remodeling,
177 further demonstrating that DVE-1 coordinates the removal of juvenile postsynaptic sites in DD
178 neurons. Interestingly, mutation of *dve-1* did not significantly affect the formation of new ventral
179 postsynaptic sites on DD neurons during remodeling or their stability (**Figure 1E,G; Figure**
180 **S1.3B**). Likewise, mutation of *dve-1* had little effect on the density of recently characterized DD
181 dendritic spines that are formed after remodeling (**Figure S1.3C,D**) [31-33]. These findings
182 indicate that the evolutionarily conserved transcription factor DVE-1 specifically governs the
183 elimination of juvenile postsynaptic sites during remodeling without affecting the formation or
184 maturation of new postsynaptic sites. Notably, the remodeling of DD GABAergic presynaptic
185 terminals also occurred normally in *dve-1* mutants (**Figure 1G**), further indicating that distinct
186 neuron-intrinsic programs direct remodeling of the pre- and postsynaptic domains of GABAergic
187 DD neurons (**Figure 1G; Figure S1.1C; Tables 1,2**).

188

189 **Lingering iAChRs in *dve-1* mutants are organized into structural synapses**

190 To test if lingering juvenile postsynaptic sites in the dorsal nerve cord of *dve-1* mutants are
191 organized into structurally intact synapses, we first asked whether these iAChR clusters were
192 localized at the cell surface. Using an established approach for *in vivo* antibody labeling of cell
193 surface receptors [33, 34], we found that lingering iAChR clusters were visible in the dorsal cord
194 of *dve-1* mutants, but not in controls (**Figure 2A**). We also found that most iAChR clusters retained
195 in dorsal GABAergic DD processes of *dve-1* mutants were closely apposed by synaptic vesicle
196 assemblies of cholinergic DA/B axons in the dorsal nerve cord (**Figure 2B**), suggesting
197 incorporation into structural synapses.

198

199 During remodeling, cholinergic DA/B connections with DD neurons in the dorsal nerve cord are
200 removed and new DA/B connections are established with post-embryonic born ventrally directed
201 GABAergic D-class (VD) motor neurons (**Figure 1A, Figure 2C**). To investigate how the
202 remodeling of presynapses within the cholinergic DA/B axons may be affected by mutation of *dve-*
203 *1*, we expressed the photoconvertible synaptic vesicle marker Dendra2::RAB-3 in cholinergic
204 DA/B neurons (**Figure 2D**). We first examined the distribution of Dendra2::RAB-3 in the wild type
205 dorsal nerve cord immediately prior to the onset of DD remodeling (approximately 14 hours after
206 hatch) (**Figure 2E**). Prior to photoconversion, clusters of green Dendra2::RAB-3 fluorescence
207 were distributed along the length of cholinergic axons in the dorsal nerve cord. Brief exposure of
208 the dorsal nerve cord to 405 nm light produced immediate and irreversible photoconversion of
209 Dendra2::RAB-3 signals from green to red fluorescence (**Figure S2.1E**). In wild type,
210 Dendra2::RAB-3 clusters that had been photoconverted to red fluorescence prior to the onset of
211 remodeling were strikingly reduced following remodeling (10 hours later, 55 ± 9% reduction) and
212 were replaced by new synaptic vesicle clusters (green fluorescence) (**Figure 2E,F; Figure**
213 **S2.1A,B,E**). In contrast, wild type Dendra2::RAB-3 clusters photoconverted after completion of
214 remodeling (at approximately 24 hours after hatch) remained largely stable over the subsequent

215 10 hours (**Figure 2G-H**, **Figure S2.1F**). We also noted the appearance of green RAB-3 clusters
216 during this time frame (24-34 hours after hatch), indicating parallel addition of new vesicular
217 material (**Figure S2.1C,D,F**). Thus, synaptic vesicle clusters in wild type DA/B axons are largely
218 removed and replaced during the 10-hour period of remodeling but are more stable over a 10-
219 hour time window immediately following completion of remodeling, offering intriguing evidence for
220 developmental stage-specific regulation of cholinergic synaptic vesicle stability. Importantly, this
221 transient reorganization of presynaptic release sites in wild type cholinergic axons occurs
222 concurrently with the removal and remodeling of postsynaptic sites in DD GABAergic neurons.
223

224 We noted a striking change in the stability of synaptic vesicle material in cholinergic axons of *dve-*
225 *1* mutants during remodeling. Dorsal cholinergic Dendra2::RAB-3 clusters photoconverted prior
226 to the onset of synaptic remodeling were preserved throughout remodeling in *dve-1* mutants
227 (**Figure 2E,F; Figure S2.1E**), indicating enhanced stability of cholinergic terminals presynaptic to
228 DD neurons. The addition of new synaptic vesicles during this time frame (14-24 hours after hatch)
229 was not appreciably affected by mutation of *dve-1*, as indicated by similar increases in green
230 Dendra2::RAB-3 fluorescence across wild type and *dve-1* mutant cholinergic axons (**Figure**
231 **S2.1A,B,E**). RAB-3 clusters that were photoconverted after the completion of remodeling
232 (approximately 24 hours after hatch) remained detectable 10 hours later in *dve-1* mutants, also
233 similar to wild type (**Figure 2G,H; Figure S2.1F**). Dorsal axon green Dendra2::RAB-3
234 fluorescence was increased by roughly 2-fold in *dve-1* mutants compared to wild type 24-34 hours
235 after hatch, suggesting enhanced addition or stabilization of new synaptic vesicles at *dve-1*
236 mutant cholinergic axon terminals after remodeling (**Figure S2.1C,D,F**). To explore this in more
237 detail, we examined the distribution of the synaptic vesicle marker SNB-1::GFP in dorsal
238 cholinergic axons of L4 stage *dve-1* mutants. The intensity of SNB-1::GFP clusters was increased
239 in dorsal cholinergic axons of *dve-1* mutants compared to wild type (**Figure 2I**), whereas SNB-

240 1::GFP fluorescence intensity in ventral cholinergic axons of *dve-1* mutants was unchanged
241 (**Figure 2J**). These data suggest DVE-1 specifically regulates cholinergic synaptic contacts onto
242 DD neurons (**Figure S2.1E**). Notably, UNC-10::GFP fluorescence intensity (labeling active zones)
243 in L4 stage dorsal cholinergic axons was not appreciably affected by *dve-1* mutation (**Figure**
244 **S2.1E**). Thus, mutation of *dve-1* leads to an increase in the stability or recruitment of synaptic
245 vesicle material at dorsal cholinergic axon terminals but does not appreciably alter the size or
246 density of active zones. Together with our previous findings, these data suggest that wild type
247 *dve-1* promotes destabilization of both vesicle assemblies in presynaptic cholinergic axons and
248 cholinergic postsynaptic sites in GABAergic neurons during remodeling.

249

250 **A failure to eliminate postsynaptic sites via DVE-1 leads to enhanced activity and altered**
251 **motor behavior**

252 To investigate how a failure of synapse elimination may impact circuit function, we first sought to
253 determine whether preserved structural connections between dorsal cholinergic axons and
254 GABAergic DD neurons of *dve-1* mutants were functional in adults. To address this question, we
255 used combined cell-specific expression of Chrimson for cholinergic depolarization [35, 36] and
256 GCaMP6 for monitoring [Ca^{2+}] changes in the postsynaptic GABAergic motor neurons [37]
257 (**Figure S3.1A**). We recorded Ca^{2+} transients from young adult GABAergic DD or VD motor
258 neurons in response to presynaptic DA/B cholinergic depolarization. We did not observe an
259 appreciable change in the magnitude of stimulus-elicited Ca^{2+} transients in VD neurons but noted
260 striking changes in DD neurons. Specifically, we found that photostimulation elicited a modest
261 Ca^{2+} response in roughly 37% of wild type DD neurons tested, consistent with a low degree of
262 synaptic connectivity between these neurons in adults as predicted by the wiring diagram [15,
263 38]. The percentage of responsive DD neurons (85%) and the average magnitude of stimulus-

264 elicited Ca^{2+} transients increased significantly for *dve-1* mutants (**Figure 3A**), demonstrating
265 enhanced functional connectivity between dorsal cholinergic neurons and GABAergic DD
266 neurons of adult *dve-1* mutants.

267 We next asked how altered functional connectivity in the motor circuit of *dve-1(uf171)* mutants
268 might affect circuit performance and behavior. Automated tracking of single worms during
269 exploratory behavior showed *dve-1(uf171)* mutants frequently moved in loose, dorsally directed
270 circles, whereas wild type animals were more likely to adopt straight trajectories (**Figure 3B**).
271 During 5 minutes of continuous tracking, roughly 80% of *dve-1(uf171)* mutants circled or curved,
272 approximately 60% of these in the dorsal direction, while only 20% of wild type circled (**Figure**
273 **3B,C**). The dorsal circling behavior of *dve-1* mutants suggested that altered synaptic output from
274 the motor circuit may produce a turning bias. In addition to GABAergic neurons, dorsally directed
275 DA/B cholinergic motor neurons are presynaptic to body wall muscles. We speculated that the
276 increased abundance of cholinergic synaptic vesicles in dorsal motor axons of *dve-1* mutants may
277 enhance cholinergic activation of dorsal muscles and elicit more robust dorsal turning. In support
278 of this idea, we found that *dve-1* mutants were hypersensitive to the paralyzing effects of the
279 acetylcholinesterase inhibitor aldicarb, an indicator of elevated acetylcholine release [39] (**Figure**
280 **S3.1B**).

281 To explore this further, we tracked animals during depolarization of dorsal cholinergic neurons by
282 cell-specific photoactivation using Chrimson. Prior to stimulation, control animals moved in
283 predominantly forward trajectories (**Figure 3D-F**). As expected, photostimulation of DA/B motor
284 neurons (625 nm, 14 mW/cm^2) enhanced dorsal turning in control animals, often leading to large
285 dorsally oriented circles (**Figure 3D,G**). DA/B motor neuron photostimulation elicited heightened
286 turning responses in *dve-1* mutants, increasing dorsal turns by ~2.5 fold compared with
287 photostimulation in wild type and leading to tight dorsally oriented circles (**Figure 3D-H**). The
288 enhanced dorsal turning of *dve-1* mutants was associated with an increase in the depth of dorsal

289 bends compared to wild type (**Figure 3G,H, Figure S3.1C,D**) and was not observed in animals
290 that lacked Chrimson expression or in the absence of retinal chromophore (**Figure S3.1E,F**).
291 Chrimson expression was also not appreciably different across *dve-1* mutants and controls
292 (**Figure S3.1G**). We propose that increased acetylcholine release onto dorsal muscles of *dve-1*
293 mutants enhances dorsal bending and circling, perhaps due to an increase in the size of the
294 synaptic vesicle pool in dorsal cholinergic axons. This interpretation is consistent with the
295 increased abundance of synaptic vesicle material in dorsally projecting cholinergic axons of *dve-*
296 *1* mutants. Ectopic activation of dorsally projecting GABAergic DD neurons in *dve-1* mutants might
297 be expected to enhance dorsal inhibition, countering the effects of dorsal excitation. However, we
298 speculate that the number and strength of synaptic connections from dorsal cholinergic motor
299 neurons to dorsal body wall muscles overwhelms any increase in dorsal inhibition. Together, our
300 results suggest mutation of *dve-1* impacts functional connectivity both through retention of juvenile
301 connectivity onto DD motor neurons and through an increase in cholinergic transmission onto
302 dorsal muscles.

303

304 **Synapse elimination occurs through a convergence of DVE-1 regulated destabilization and**
305 **removal of OIG-1 antagonism**

306 The timing of DD neuron remodeling is, in part, determined through temporally controlled
307 expression of the Ig-domain protein OIG-1 [24, 33]. The expression of an *oig-1pr::*GFP
308 transcriptional reporter in L1 stage DD neurons was not appreciably altered in *dve-1* mutants
309 (**Figure 4A**), in alignment with prior evidence that *oig-1* expression is regulated independently of
310 *dve-1*. The Ig domain protein OIG-1 normally antagonizes synaptic remodeling. In *oig-1* mutants,
311 the remodeling of postsynaptic sites in DD neurons, including both elimination of dorsal juvenile
312 postsynaptic sites and the formation of new ventral postsynaptic sites, occur precociously

313 compared with wild type [23, 24]. However, unlike the precocious removal of dorsal postsynaptic
314 sites in DD neurons of *oig-1* mutants, the removal of dorsal postsynaptic sites in *oig-1*;*dve-1*
315 double mutants was strikingly delayed. The juvenile dorsal postsynaptic sites were retained in DD
316 neurons of *oig-1*;*dve-1* mutants through late L4 stage, similar to *dve-1* single mutants (**Figure 4B-**
317 **C,F**). DVE-1 is therefore required for synapse elimination even under conditions where
318 antagonistic processes promoting synapse stabilization are disrupted. Conversely, similar to the
319 premature formation of new ventral postsynaptic sites in *oig-1* single mutants, ventral synapses
320 formed precociously in *oig-1*;*dve-1* double mutants (**Figure 4D-E, F**). Thus, disruption of *dve-1*
321 function reversed precocious synapse elimination in *oig-1* mutants but did not impact the
322 premature assembly of ventral postsynaptic sites, supporting the independence of programs for
323 synapse elimination versus growth and suggesting independent functions for OIG-1 in each
324 (**Figure 4F,G**). Overall, our findings show that mature connectivity is sculpted through a
325 convergence of DVE-1 regulated elimination processes and temporally regulated OIG-1 based
326 stabilization mechanisms.

327

328 **DVE-1 localization to GABAergic nuclei is required for synapse elimination**

329 To better understand potential mechanisms for DVE-1 actions in synapse elimination, we
330 examined *dve-1* expression using a strain where a GFP coding sequence was inserted in the *dve-*
331 *1* genomic locus [40]. As noted previously [40], we observed prominent expression of
332 endogenously labeled DVE-1::GFP in intestinal cells. However, we also noted neuronal
333 expression of DVE-1::GFP in roughly 20 neurons at the L1 stage prior to remodeling [41]. Notably,
334 in the ventral nerve cord, DVE-1 was solely expressed in DD GABAergic neurons (**Figure 5A,B**).
335 Further, DVE-1 was specifically localized to GABAergic nuclei, where it assembled in discrete
336 nuclear foci during the time frame of synaptic remodeling. Similar nuclear DVE-1 clusters have

337 been observed in intestinal cell nuclei where DVE-1 is thought to regulate gene expression during
338 the mitochondrial unfolded protein response (mtUPR) by associating with loose regions of
339 chromatin and organizing chromatin loops [40]. DVE-1 localization to GABAergic nuclei raises the
340 possibility that DVE-1 mediates its effects by regulating gene programs required for synapse
341 elimination in GABAergic neurons. DVE-1::GFP expression in GABAergic neurons required the
342 Pitx family homeodomain transcription factor UNC-30, the terminal selector of *C. elegans*
343 GABAergic motor neuron identity (**Figure S5.1A**) [42-44]. Consistent with this observation,
344 putative UNC-30 binding sites [42-44] are present within the DVE-1 promoter region. Interestingly,
345 mutation of *unc-30* produced no appreciable change in DVE-1::GFP fluorescence in intestinal
346 cells, indicating cell type-specific mechanisms for *dve-1* expression mediated at least in part
347 through UNC-30 regulation (**Figure S5.1B**).

348 Prior studies of DVE-1 in intestinal cells showed that deSUMOylation of DVE-1, mediated by the
349 isopeptidase ULP-4, is required for its nuclear localization [45]. To explore whether DVE-1
350 localization to DD GABAergic nuclei is important for DVE-1 regulation of synapse elimination, we
351 asked if the nuclear localization of DVE-1 in GABAergic neurons is also regulated by ULP-4. We
352 observed that mutation of *ulp-4* caused a striking decrease of nuclear *dve-1::*GFP fluorescence
353 in GABAergic neurons and severely diminished *dve-1::*GFP nuclear foci (**Figure 5B,C**). A mutated
354 form of DVE-1::GFP, DVE-1K327R, where a key lysine residue required for SUMOylation is
355 mutated to arginine [45], localized to GABAergic nuclei in the absence of *ulp-4* (**Figure 5B,C**).
356 Together, these data demonstrate that nuclear localization of DVE-1 in GABAergic neurons is
357 regulated by ULP-4 and SUMOylation. Importantly, we found that ULP-4 was also required for
358 the elimination of dorsal iAChR clusters during remodeling, such that dorsal iAChR clusters
359 remained present in roughly 50% of L4 stage *ulp-4* mutant animals (**Figure 5D-F**). Either pan-
360 neuronal or GABA neuron-specific expression of the wild type *ulp-4* gene in *ulp-4* mutants was
361 sufficient to restore the elimination of dorsal iAChRs, while intestinal *ulp-4* expression was not

362 (**Figure 5D-F**). Further, mutation of the DVE-1 SUMOylation site (K327R) by itself did not impair
363 synapse elimination but restored proper removal of iAChRs in *ulp-4* mutants (**Figure 5D-E**). We
364 conclude that the localization of DVE-1 to GABAergic nuclei is essential for synapse elimination
365 during remodeling, and this localization is regulated at least in part by SUMOylation. Notably, the
366 nuclear localization of mammalian SATB family members is also dependent on SUMOylation,
367 suggesting conserved regulatory mechanisms [46, 47].

368

369 **Analysis of DVE-1 transcriptional targets reveals several pathways with relevance for**
370 **synapse elimination**

371 Recent work revealed that homeodomain transcription factors are broadly utilized in the
372 specification of *C. elegans* neuronal identity [41]. Given this finding and DVE-1 homology with
373 mammalian SATB family transcription factors, we asked whether DVE-1 transcriptional regulation
374 may be important for GABAergic neuronal identity. We found that the numbers of DD neurons
375 and commissures were unchanged in *dve-1* mutants compared to wild type (**Figure S6.1A**). In
376 addition, we found that the expression levels for *oig-1* (**Figure 4A**) and three additional GABAergic
377 markers in DD neurons (*unc-47*/GABA vesicular transporter, *unc-25*/glutamic acid decarboxylase,
378 and *flp-13*/FMRFamide neuropeptide) were not appreciably altered by *dve-1* mutation (**Figure**
379 **S6.1B**). These results support that DVE-1 is not critical for GABAergic identity of the DD neurons
380 but instead regulates other aspects of GABAergic neuron development, such as the transcription
381 of effectors important for synapse elimination.

382

383 To reveal potential direct targets of DVE-1 in GABAergic neurons, we analyzed chromatin
384 immunoprecipitation followed by sequencing (ChIP-Seq) data available from the modENCODE
385 consortium [48]. We found 1044 genes with strong DVE-1 binding signal in their promoter regions,

386 implicating these genes as potential direct targets of DVE-1 transcriptional regulation (**File S5**).
387 We noted that 627 of these genes are significantly expressed in GABAergic neurons based on
388 available single-cell RNA-seq data (**File S5**) [49, 50]. Pathway analysis of the GABAergic neuron-
389 enriched targets using WormCat [51] and WormenrichR [52] revealed a significant enrichment of
390 genes involved in the mitochondrial unfolded protein response (mtUPR) stress pathway (**Figure**
391 **6A, File S5)**, as expected from prior studies [27, 45, 53]. Notably, our analysis also revealed
392 enrichment of genes involved in the ubiquitin-proteasome system as well as various other
393 processes including ribosomal composition, and endocytic and phagocytotic function (**Figure 6A,**
394 **B, Table 3 File S5**). These pathways represent intriguing potential targets for DVE-1-dependent
395 regulation in the control of synapse elimination.

396

397 **Inhibition of the ubiquitin-proteasome system, but not activation or inhibition of mtUPR,**
398 **delays DVE-1-dependent synapse elimination**

399 To clarify which of the pathways identified from our analysis may be most critical, we next asked
400 whether DVE-1 regulates synapse elimination by activating or inhibiting the mtUPR. We first
401 quantified the length and density of mitochondria in DD neurons and found no differences
402 between wild type and *dve-1* mutants (**Figure S6.2A**). We next measured mtUPR activation in
403 *dve-1* mutants by quantifying the fluorescence of *hsp-6pr::*GFP, a commonly used mtUPR
404 reporter [27]. Surprisingly, we noted increased levels of intestinal *hsp-6pr::*GFP expression in *dve-*
405 *1* mutants compared with control, suggesting elevated mtUPR activity (**Figure S6.2B, C**). The
406 transcription factor ATFS-1 is required for the expression of *hsp-6pr::*GFP transcriptional
407 response and activation of the mtUPR [54]. RNAi knockdown of *atfs-1* decreased *hsp-6pr::*GFP
408 expression in *dve-1* mutants (**Figure S6.2C**), indicating that downregulation of *atfs-1* reduced the
409 mtUPR. However, inhibition of the mtUPR by *atfs-1* knockdown failed to restore normal removal

410 of dorsal iAChR clusters in *dve-1* mutants (**Figure S6.2D**). Likewise, a null mutation in *atfs-1* did
411 not alter synapse elimination in otherwise wild type animals and failed to restore synapse
412 elimination when combined with mutation of *dve-1* in *atfs-1;dve-1* double mutants (**Figure 6C**).
413 These results show that increased activation of the mtUPR in *dve-1* mutants is not sufficient to
414 account for a failure in synapse removal. Consistent with this interpretation, constitutive mtUPR
415 activation by mutation of the mitochondrial complex III subunit gene *isp-1* also did not alter
416 synapse elimination (**Figures 6C and S6.2D**) [55]. Additionally, mutation of *ubl-5*, a cofactor with
417 DVE-1 in the initiation of the intestinal mtUPR [56], did not affect synapse elimination (**Figure 6C**).
418 Our findings demonstrate that mtUPR activation or inhibition do not alter synapse removal. We
419 conclude that DVE-1 coordinates synapse elimination through transcriptional regulation of
420 alternate pathways, perhaps those identified from our enrichment analysis (**Figure 6A,B**).

421 Given recent evidence for the regulation of synapse structure through ubiquitin-dependent
422 degradation processes and links with neurological disease [57], we next asked whether DVE-1
423 control of synapse elimination may occur through transcriptional regulation of ubiquitin-
424 proteasome function. We investigated the requirement for the ubiquitin proteasome system (UPS)
425 during synapse elimination using bortezomib, a small molecule inhibitor of the 26S proteasome.
426 While treatment with high (≥10 μM) concentrations of bortezomib produced larval arrest, treatment
427 with 5 μM bortezomib was sufficient to disrupt UPS function, as assessed by induction of the *skn-*
428 *1* dependent proteasome reporter *rpt-3pr::*GFP [58] (**Figure S6.2E**), without causing
429 developmental arrest. Moreover, treatment with 5 μM bortezomib significantly delayed synapse
430 elimination during remodeling. Specifically, more than 50% of animals treated with bortezomib
431 failed to remove juvenile dorsal postsynaptic sites in DD neurons by 24 hrs after hatch **(Figure**
432 **6D-F)**, demonstrating a requirement for UPS function in synapse elimination. The identification of
433 UPS pathway genes as targets for transcriptional regulation by DVE-1 therefore leads us to
434 propose that DVE-1 control of synapse elimination during remodeling occurs at least in part

435 through transcriptional regulation of the ubiquitin proteasome system in DD GABAergic neurons

436 (**Figure 6G**).

437

438 **Discussion**

439 Developmental remodeling of synaptic connectivity occurs throughout phylogeny, refining and
440 reorganizing neuronal connections toward the establishment of the mature nervous system. While
441 neuron-extrinsic events that shape remodeling, for example, microglial phagocytosis of synaptic
442 material [5-8], have gained a lot of recent attention, neuron-intrinsic processes governing
443 remodeling have remained less well-described. Likewise, the relationship between degenerative
444 and growth processes during remodeling have not been clearly elucidated. The developmental
445 remodeling of *C. elegans* GABAergic DD neurons presents a uniquely accessible system for
446 addressing important questions about evolutionarily conserved neuron-intrinsic mechanisms of
447 remodeling because the reorganization of their connectivity occurs without gross morphological
448 changes or a requirement for synaptic removal by other cell types.

449 Here, we show that the homeodomain transcription factor *dve-1* with homology to the SATB family
450 of transcription factors is specifically required for the elimination of juvenile synaptic inputs to DD
451 neurons during remodeling. In *dve-1* mutants, juvenile postsynaptic sites and apposing
452 cholinergic presynaptic terminals are preserved into adulthood. The failure to eliminate these sites
453 results in elevated activity at these synapses and impaired motor function. Interestingly, *dve-1* is
454 not required for the growth of new DD neuron synaptic inputs that are characteristic of the mature
455 motor circuit, indicating that the formation of new connections is not dependent upon elimination
456 of pre-existing juvenile synapses. Likewise, mutation of *dve-1* does not alter developmental
457 reorganization of synaptic outputs from DD neurons onto muscles. In *dve-1* mutants, newly
458 relocated GABAergic synaptic terminals occupy similar territories in DD neurons as lingering
459 juvenile synaptic inputs. Thus, the formation of new GABAergic presynaptic terminals during
460 maturation of the circuit is not contingent on elimination of nearby juvenile postsynaptic sites in
461 DD neurons.

462 Our findings lead us to propose that cell-autonomous transcriptional regulation of GABAergic
463 neurons by DVE-1 promotes the elimination of their juvenile synaptic inputs. We found that DVE-
464 1 is expressed in a limited number of neurons, including GABAergic motor neurons, and DVE-1
465 localization to GABAergic nuclei is required for synapse elimination to proceed normally. DVE-1
466 regulation of synapse elimination shares interesting parallels with a previously described pathway
467 for elimination of postsynaptic structures at mouse glutamatergic synapses through transcriptional
468 regulation by Myocyte Enhancer Factor 2 (Mef2) [59, 60]. However, in contrast to MEF2-regulated
469 synapse elimination, we found that DVE-1-dependent elimination is not strongly activity-
470 dependent. Also, we did not observe strong temporal regulation of DVE-1 expression in
471 GABAergic neurons prior to or during remodeling, raising important mechanistic questions about
472 the timing of synapse elimination. One possible route for temporal regulation might be through
473 control of DVE-1 nuclear localization. We show that DVE-1 localization to GABAergic nuclei can
474 be regulated through SUMOylation. However, we observed nuclear localization of DVE-1 in
475 GABAergic neurons prior to the onset of remodeling, suggesting the presence of additional
476 mechanisms for temporal control. This is consistent with prior work indicating that temporally
477 controlled expression of OIG-1 regulates the timing of remodeling [23, 24]. We found that
478 precocious synapse elimination in *oig-1* mutants is reversed when *dve-1* function is also
479 disrupted, further indicating that DVE-1 transcriptional regulation is required for synapse
480 elimination to occur. In contrast, precocious growth of new synapses in *oig-1* mutants was not
481 altered by mutation of *dve-1*, suggesting that DVE-1 regulated degenerative mechanisms act in
482 parallel with growth processes that are regulated independently (**Figure 6G**).

483

484 Our experiments show that mutation of *dve-1* affects the stability of both postsynaptic sites in DD
485 GABAergic neurons and presynaptic terminals in cholinergic neurons. We show that the juvenile
486 synaptic vesicle assemblies in axons of presynaptic cholinergic neurons are almost completely

487 exchanged during the 10-hour period of wild type remodeling. This turnover of synaptic vesicles
488 during remodeling contrasts with the relative stability of wild type synaptic vesicles over the 10
489 hours immediately following remodeling. Thus, turnover of synapse-associated vesicles in
490 presynaptic cholinergic axons occurs at a higher rate during circuit rewiring, suggesting temporal
491 regulation of an active process for presynaptic reorganization. Notably, removal of juvenile
492 synaptic vesicle assemblies during remodeling is strikingly reduced in *dve-1* mutants, indicating
493 that disruption of DVE-1 transcriptional activity is sufficient to stabilize presynaptic vesicle pools
494 in cholinergic neurons. Since DVE-1 is solely expressed in postsynaptic GABAergic neurons, our
495 results suggest that DVE-1-regulated postsynaptic pathways promote exchange or elimination of
496 juvenile presynaptic elements through destabilization of the postsynaptic apparatus. Our
497 photoconversion experiments also show that recruitment of new synaptic vesicles in cholinergic
498 axons of *dve-1* mutants is not halted by the stabilization of juvenile synaptic vesicle assemblies.
499 We noted an overall increase in dorsal synaptic vesicle material in *dve-1* mutants compared with
500 either wild type or ventral synapses of *dve-1* mutants. Our Ca^{2+} imaging and behavioral
501 experiments provide evidence that the increase in cholinergic synaptic vesicles of dorsally
502 projecting motor neurons alters circuit function such that cholinergic activation of dorsal
503 musculature is enhanced in *dve-1* mutants, resulting in deeper dorsal bends and a dorsal turning
504 bias during movement.

505 Our pathway analysis of DVE-1 ChIP-seq data showed a high enrichment of genes involved in
506 the mtUPR. In the mtUPR, DVE-1/SATB is thought to organize loose chromatin to induce
507 expression of chaperones and proteases [27, 53, 56]. However, manipulations that either
508 activated or inhibited the mtUPR did not affect remodeling, providing support for a model where
509 DVE-1 regulation of remodeling is distinct from DVE-1 function in mtUPR. In addition to the
510 mtUPR, our analysis of DVE-1 targets revealed enrichment of genes in other pathways that may
511 represent alternative targets of DVE-1 for removal of synapses, in particular UPS pathway genes.

512 Notably, inhibition of proteasome function caused a striking reduction in synapse elimination,
513 supporting involvement of this pathway and suggesting that DVE-1 transcriptional regulation of
514 the proteasome may be important to promote synapse elimination.

515 The closest homolog of DVE-1 is the *Drosophila* homeodomain transcription factor *defective*
516 *proventriculus* (*Dve*). Interestingly, transcriptional profiling of *Drosophila* mushroom body gamma
517 neurons during their remodeling showed Dve expression peaks at the onset of remodeling
518 (https://www.weizmann.ac.il/mcb/Schuldiner/resources) [61]. DVE-1 also shares homology with
519 the mammalian chromatin organizers special AT-rich sequence-binding (SATB) proteins 1 and 2.
520 The SATB family of transcriptional regulators have been shown to play roles in many areas of
521 mammalian brain development, such as the activation of immediate early genes important for
522 maintaining dendritic spines in GABAergic interneurons [62] and cortex development and
523 maturation [63], but roles in synapse elimination had been previously uncharacterized. Our
524 findings offer a striking example of DVE-1/SATB transcriptional activation of pro-degenerative
525 pathways acting in concert with temporally controlled expression of a maintenance factor to
526 control a developmentally defined period of synapse elimination. Given the conservation of DVE-
527 1 and the mammalian SATB family of transcriptional regulators, our analysis may point toward
528 new mechanisms by which SATB family transcription factors control brain development.
529 Importantly, dysfunction of these transcription factors in humans, as in SATB2-associated
530 syndrome, is characterized by significant neurodevelopmental delays, limitations in speech, and
531 severe intellectual disability [64, 65] . More broadly, our findings highlight a cellular strategy for
532 temporal control of circuit development through convergent regulation of antagonistic cellular
533 processes. Interestingly, spatiotemporal regulation through competing parallel transcriptional
534 programs is utilized in other developmental contexts across different species [66-68], suggesting
535 this represents a broadly utilized mechanism for temporal control of key developmental events.

536 **Methods**

537 Strains and Genetics

538 All strains are derivatives of the N2 Bristol strain (wild type) and maintained under standard
539 conditions at 20-25°C on nematode growth media plates (NGM) seeded with *E. coli* strain OP50.
540 Some strains were provided by the *Caenorhabditis* Genetics Center, which is funded by NIH
541 Office of Research Infrastructure Programs (P40 OD010440), and by the National BioResource
542 Project which is funded by the Japanese government. Transgenic strains were generated by
543 microinjection of plasmids or PCR products into the gonad of young hermaphrodites. Integrated
544 lines were produced by X-ray irradiation or UV-integration and outcrossed to wild type/N2 Bristol.
545 A complete list of all strains used in this work is included in supplemental file 1.

546

547 Molecular Biology

548 Plasmids were constructed using two-slot Gateway Cloning system (Invitrogen) and confirmed by
549 restriction digest and/or sequencing as appropriate. All plasmids and primers used in this work
550 are described in supplemental file 2 and 3 respectively.

551 To generate the DVE-1 genomic rescue the *dve-1* promoter (5 kb upstream from translational
552 start site), genomic fragment (from translational start to stop, 6107bp), and *dve-1* 3' UTR (626bp
553 downstream from translational stop) were amplified from genomic N2 DNA. pKA110 (*unc-*
554 *129pr*::Dendra2::RAB-3) was created by ligating a gBlock (IDT) containing the Dendra2 coding
555 sequence into NheI-HF/PstI-HF digested pDest-114 to generate pDest-339 (Dendra2::RAB-3).
556 pDest-339 was then recombined with pENTR-*unc-129* to generate pKA110 and injected at 50
557 ng/µl. To generate pKA35 (*unc-129pr*::Chrimson::SL2::BFP) Chrimson was amplified from pDest-
558 104 and ligated into NheI-HF/BstBI digested pDest-239 to generate pDest-240

559 (Chrimson::SL2::BFP). pDest-240 was then recombined with pENTR-*unc-129* to generate pKA35
560 and injected at 50 ng/µl.

561 To generate ULP-4 rescue constructs ULP-4 cDNA was amplified from RNA and ligated into NheI-
562 HF/KpnI-HF digested pDest-139 to generate pDest-291(ULP-4cDNA). pDest-291 was
563 recombined with pENTR-*unc-47* to generate pKA76 (*unc-47pr*::ULP-4cDNA), pENTR-F25B3.3 to
564 generate pKA78 (F25B3.3pr::ULP-4cDNA), and pENTR-*gly-19* to generate pKA80 (*gly-*
565 *19pr::*ULP-4cDNA). All *ulp-4* rescue constructs were injected at 30 ng/µl.

566 pKA74 (*unc-47pr*::NLS::mCherry) was created by amplifying an artificial intron and NLS from
567 plasmid #68120 (Addgene) and was ligated into AgeI-HF/XbaI digested pDest-145 to generate
568 pDest-205(NLS::mCherry). pDest-205 was recombined with pENTR-*unc-47* to generate pKA74
569 and injected at 50 ng/µl.

570

571 Staging time course DD remodeling

572 Briefly, freshly hatched larvae were transferred to seeded OP50 plates and maintained at 25°C
573 (timepoint 0). Imaging and analysis of iAChR or synaptic vesicle remodeling was assessed as
574 previously described [23].

575

576 Confocal imaging and analysis

577 Unless noted otherwise, all strains were immobilized with sodium azide (0.3M) on a 2% or 5%
578 agarose pad. All confocal Images were obtained either using an Olympus BX51WI spinning disk
579 confocal equipped with a 63x objective or on the Yokogawa CSU-X1-A1N spinning disk confocal
580 system (Perkin Elmer) equipped with EM-CCD camera (Hamamatsu, C9100-50) and 63x oil

581 immersion objective. Analysis of synapse number and fluorescence intensity was performed using
582 FIJI ImageJ software (open source) using defined threshold values acquired from control
583 experiments for each fluorescent marker. Statistical analysis for all synaptic and spine analysis
584 between two groups utilized a student's t-test; for analysis where, multiple groups were compared
585 an ANOVA with Dunnett's multiple comparisons test was used.

586 *Synaptic analysis:* Background fluorescence was subtracted by calculating the average intensity
587 of each image in a region outside the ROI. All ROIs were 25 µm or 30 µm in length. Quantification
588 of the number of puncta within an ROI had a set threshold of 25-255 and the analyze particles
589 function of ImageJ was used to quantify any particle greater than 4 pixels^2. Fluorescence intensity
590 was quantified from the raw integrated fluorescence within the ROI. For quantification of the DD
591 neuron synapses the ROI was defined as either the ventral region anterior to the DD1 soma or
592 the opposing dorsal region. For quantification of the DA/DB neuron synapses the ROI was defined
593 as either the ventral region between DB1 and DB3 or the opposing dorsal region between VB1
594 and VB3.

595 *Spine/dendrite analysis:* Spine number was quantified as described previously [32, 33]. Briefly,
596 spines were counted within a 30 µm ROI anterior to the soma of DD1. Dendrite length was defined
597 as the anterior extension from DD1 soma to the end of the ventral process.

598

599 <u>EMS Screen</u>

600 The EMS mutagenesis protocol was adapted from [69]. *flp-13pr::*ACR-12::GFP strain IZ1905
601 animals were treated with 25 µM ethyl methanesulfonate (EMS, Sigma). After washing, P0
602 mutagenized animals were recovered. F1 animals were transferred to fresh plates and 8 F2s were
603 isolated per F1 (F2 clonal screen). The F3 progeny of ~400 F2s per round were screened. After

604 27 rounds of EMS, a total of 3261 haploid genomes were screened. Each isolated candidate
605 mutant was rescreened three times to confirm the phenotype.

606

607 Variant discovery mapping and whole genome sequencing

608 Mutant strains were backcrossed a single time into the IZ2302 starting strain injected with *unc-*
609 *122pr::*GFP co-injection marker(enabling the distinction of cross- from self-progeny). F2 animals
610 were isolated onto separate plates and their F3 brood were screened on a confocal microscope
611 for a remodeling phenotype. 21 independent homozygous recombinant F2 lines were thus
612 isolated and pooled together. Worm genomic DNA was prepared for sequencing following Gentra
613 Puregene Tissue Kit DNA purification protocol (Qiagen). Library construction and whole genome
614 sequencing were performed by Novogene. Briefly, NEBNext DNA Library Prep Kit was used for
615 library construction. Pair-end sequencing was performed on Illumina sequencing platform with a
616 read length of 150 bp at each end. Reads were mapped to *C. elegans* reference genome version
617 WS220 and analyzed using the CloudMap pipeline [70] where mismatches were compared to the
618 parental strain as well as to the other sequenced mutants isolated from this screen [70, 71].

619

620 Injection of fluorescent antibodies for *in vivo* labeling of iAChRs

621 For staining of iAChRs at the cell surface, mouse monoclonal α-HA antibodies (16B12 Biolegend)
622 coupled to Alexa594 were diluted in injection buffer (20 mM K_3PO_4, 3 mM K citrate, 2% PEG 6000,
623 pH 7.5). Antibody was injected into the pseudocoelom of L2/L3 stage wild type or *dve-1(uf171)*
624 animals as described previously [23, 34]. Animals were allowed to recover for six hours on seeded
625 NGM plates. Only animals in which fluorescence was observed in coelomocytes were included in
626 the analysis. A student's t-test was used for statistical analysis.

627

628 Photoconversion of Dendra2::RAB-3

629 Wild type and *dve-1(uf171)* mutant L1 animals (12-14 hours post-hatch) expressing
630 Dendra2::RAB3 were paralyzed using 1 mM Levamisole and imaged. Dendra2::RAB-3 puncta in
631 the DA/DB dorsal axonal process were photoconverted using a 405 nm laser at 800 ms for 30 s.
632 Images were acquired immediately following photoconversion and again 10 hours later. Between
633 photoconversion and next timepoint animals were rescued and allowed to recover. Both red and
634 green fluorescent signals were quantified. A student's t-test was used for statistical analysis.

635

636 Aldicarb paralysis assays

637 The aldicarb assays were performed as previously described [39]. Strains were scored in parallel,
638 with the researcher blinded to the genotype. Young adult animals (24 hours after L4) at room
639 temperature (22–24°C) were selected (>10 per trial for at least 3 trials) and transferred to a
640 nematode growth medium plate containing 1 mM aldicarb (ChemService). Movement was
641 assessed every 15 minutes for 2 hours. Animals that displayed no movement when prodded
642 (paralyzed) were noted. The percentage of paralyzed animals were calculated at each timepoint.

643

644 Calcium imaging

645 Transgenic animals expressing *ttr-39pr*::GCaMP6s::SL2::mCherry (GABA neurons) along with
646 *unc-129pr*::Chrimson::SL2::BFP (DA and DB cholinergic neurons) were grown on NGM plates
647 with OP50 containing 2.75 mM All-Trans Retinal (ATR). L4 animals (40 hours post-hatch) were
648 staged 24 hours prior to experiments on fresh ATR OP50 NGM plates. Imaging was performed

649 with 1-day age adults immobilized in hydrogel [32, 72]. Animals were transferred to 7.5 μL of the
650 hydrogel mix placed on a silanized glass slide and covered with cover slip. Hydrogel was cured
651 using a handheld UV Transilluminator (312 nm, 3 minutes). Chrimson photoactivation (~14
652 mW/cm^2) was achieved using a TTL-controlled 625 nm light guide coupled LED (Mightex
653 Systems). A 556 nm BrightLine single-edge short-pass dichroic beam splitter was positioned in
654 the light path (Semrock) [33]. Data were acquired at 10 Hz for 15 s using Volocity software at a
655 binning of 4x4. Analysis was performed using ImageJ. DD and VD GABA motor neuron cell bodies
656 were identified by mCherry fluorescence and anatomically identified by position along the ventral
657 nerve cord. Each field typically contained 1–5 GABA motor neurons. Only recordings of neurons
658 located anterior to the vulva were included in the analysis. Photobleaching correction was
659 performed on background subtracted images by fitting an exponential function to the data
660 (CorrectBleach plugin, ImageJ). Pre-stimulus baseline fluorescence (F_0) was calculated as the
661 average of the corrected background-subtracted data points in the first 4 s of the recording and
662 the corrected fluorescence data was normalized to prestimulus baseline as $\Delta F/F_0$, where $\Delta F=F-$
663 F_0. Peak $\Delta F/F_0$ was determined by fitting a Gaussian function to the $\Delta F/F_0$ time sequence using
664 Multi peak 2.0 (Igor Pro, WaveMetrics). All data collected were analyzed, including failures (no
665 response to stimulation). Peak $\Delta F/F_0$ values were calculated from recordings of >10 animals per
666 genotype. Mean peaks ± SEM were calculated from all peak $\Delta F/F_0$ data values. For all genotypes,
667 control animals grown in the absence of ATR were imaged.

668

669 Single worm tracking

670 Single worm tracking was carried out for a duration of 5 minutes, on NGM plates seeded with 50
671 μL of OP50 bacteria, using Worm Tracker 2 [73]. Animals were allowed to acclimate for 30 s prior
672 to tracking. Movement features were extracted from 5 minutes of continuous locomotion tracking.

673 Worm tracker software version 2.0.3.1, created by Eviatar Yemini and Tadas Jucikas (Schafer
674 lab, MRC, Cambridge, UK), was used to analyze movement [74]. Locomotion paths were
675 extracted from 5 minutes of continuous locomotion tracking. Scoring of path trajectories was
676 performed blinded to genotype.

677

678 Optogenetic analysis

679 Behavioral assays were performed with young adults at room temperature (22°C–24°C). Animals
680 were grown on plates seeded with OP50 containing 2.7 mM All-Trans Retinal (ATR). Animals
681 were placed on fresh plates seeded with a thin lawn of OP50 containing ATR and allowed to
682 acclimate for 1 minute. Dorsal-ventral position was noted prior to recording. Animals were allowed
683 to move freely on plates and recorded with a Mitex X camera for 1 minute before stimulus,
684 following this a Mightex LED module was used to stimulate Chrimson (625nm 14mW/cm^2)
685 continuously for 2 minutes. Locomotion (trajectory and body bending) was recorded with
686 WormLab (MBF Bioscience) software. A mid-point bending angle histogram was generated for
687 each animal such that over the span of 2 minutes body angles were measured and binned by the
688 degree of angle. Depending on starting position negative and positive degree angles were
689 assigned dorsal or ventral. Any bending angle greater than 0 but less than 50˚ was determined a
690 regular bend. We noted wild type animals without stimulus rarely make angles greater then 50˚
691 and qualified any bending angle over 50˚ as a deep bend. An ANOVA with Dunnett's multiple
692 comparisons test was used for comparisons between pre-stimulus and stimulus in wild type and
693 *dve-1(uf171)*. A Student's T-test was used when comparing number of dorsal bends greater then
694 50° in wildtype vs *dve-1* mutant animals.

695

696 RNAi by feeding

697 L4 larvae expressing *hsp-6pr::*GFP were cultured with *E. coli* expressing either control double-
698 stranded RNA (empty vector) or targeting *atfs-1* and progeny were allowed to develop to L4 stage
699 at 20°C. Intestinal GFP fluorescence of L4 stage progeny was measured using the Zeiss Imager
700 M1, 10x objective.

701

702 CRISPR/Cas9 K327R

703 Strain IZ4473 *dve-1(uf206)* was generated in *syb1984* (DVE-1 CRISPR-Cas9-mediated GFP
704 knock, Tian lab) animals. A K-R mutation was created by changing AAA to CGT in exon 6, 4783
705 bp downstream of start. The IDT CRISPR HDR design tool
706 (https://www.idtdna.com/pages/tools/alt-r-crispr-hdr-design-tool) was used to generate repair
707 templates and guide sequences. Animals were injected with CRISPR/Cas9 mix [crRNA (oligo
708 2nmol, IDT), Donor (oligo 4nmol, IDT), purified Alt-R S.p. Cas9 nuclease V3 100µg (IDT CAT
709 1081058), Alt-R CRISPR/Cas9 tracrRNA (5nmol, IDT CAT 1072532), and pRF-4 (*rol-6* plasmid)].
710 Rolling worms were singled and validated by PCR sequencing. CRISPR/Cas9 design is provided
711 in supplemental file 4.

712

713 DVE-1 nuclear localization

714 DVE-1::GFP was measured in L1 stage DD nuclei using the strain *syb1984* (DVE-1 CRISPR-
715 Cas9-mediated GFP knock in); *ufEx1814*(*unc-47pr::NLS::mCherry*). ROIs were determined by
716 expression of the nuclear localized mCherry signal. Within the ROI a segmented line was drawn
717 through the nucleus and an intensity profile was created for each nucleus. Fluorescence intensity
718 values for DVE-1::GFP were quantified by averaging the largest 5 intensity values at the peak
719 (roughly 0.5 µm). At least 2 DD nuclei per animal were analyzed. ANOVA with Dunnett's multiple

720 comparison test was used for statistical analysis. For analysis of *unc-30* mutants, an ROI was
721 selected from the base of the pharynx out posteriorly by 30µm. For consistent analysis red GABA
722 neurons within the head, unaffected by *unc-30* mutation and the pharynx served as landmarks for
723 both wild type and *unc-30* mutant animals. Students t-test was used for statistical analysis.

724

725 ChIP-seq data acquisition from ModEncode

726 modENCODE (www.modencode.org) produced ChIP-seq data by immunoprecipitating GFP from
727 a line expressing DVE-1::GFP that was stably integrated into the genome. The DVE-1 ChIP-seq
728 data set included two biological replicates at the late embryo stage as well as control animals.
729 Significant peaks were called using PeakSeq and only peaks that were identified in both biological
730 replicates were considered for analysis. DVE-1::GFP ChIP-seq data and experimental details can
731 be found at http://intermine.modencode.org/release-33/report.do?id=77000654 (DCCid:
732 modENCODE_4804) [75, 76]. Peaks were considered mapped to genes if there was at least an
733 80% overlap between the peak maximum read density and the region within 1kb base pairs
734 upstream of the genes annotated transcriptional start site using the UCSC table browser intersect
735 function [77].

736

737 Pathway analysis

738 Pathway analysis was performed using both WormCat [51]: http://www.wormcat.com, and the
739 enrichment analysis tool WormenrichR [52, 78]: https://amp.pharm.mssm.edu/WormEnrichr/.
740 For WormCat analysis pathways were considered enriched if they had a p-value < 0.01 and
741 Bonferroni FDR < 0.01. The WormEnrichR pathway enrichment analysis utilized the
742 WikiPathway database [79]. For WormEnrichR, pathways were considered enriched if they had

743 a p-adj < 0.05 and a combined score >10.

744 Bortezomib time course

745 Worms were hatched synchronously on NGM plates at 25°C. Animals were transferred to 5μM
746 Bortezomib (MilliporeSignma) plates at 10 hours post-hatch and allowed to develop until imaging
747 at 24 hours post-hatch.

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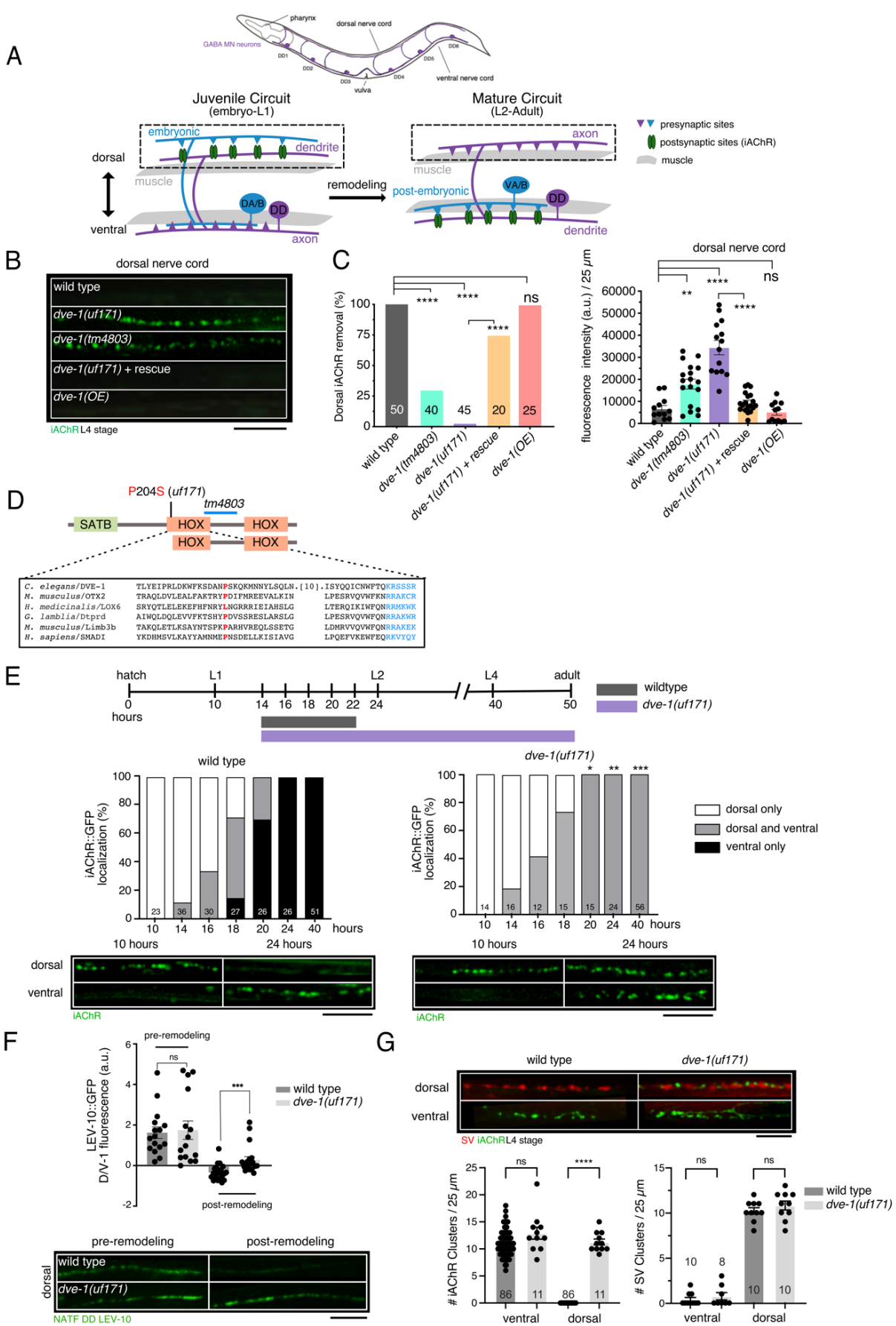

A
pharynx
dorsal nerve cord
GABA MN neurons
DD1
DD2
DD3
DD4
DD5
DD6
vulva
ventral nerve cord
Juvenile Circuit
(embryo-L1)
Mature Circuit
(L2-Adult)
embryonic
dendrite
dorsal
muscle
DA/B
DD
ventral
axon
remodeling
post-embryonic
VA/B
presynaptic sites
postsynaptic sites (iAChR)
muscle
B
dorsal nerve cord
wild type
dve-1(uf171)
dve-1(tm4803)
dve-1(uf171) + rescue
dve-1(OE)
iAChR L4 stage
C
Dorsal iAChR removal (%)
50
40
45
20
25
wild type
dve-1(tm4803)
dve-1(uf171)
dve-1(uf171) + rescue
dve-1(OE)
fluorescence intensity (a.u.) / 25 µm
dorsal nerve cord
D
P204S (uf171)
tm4803
SATB
HOX
C. elegans/DVE-1 TLYEIPRLDKWFKSDANPSKQKMNNYLSQLN.[10].ISYQQICNWFTQKRSSSR
N. musculus/OTX2 TRAQLDVLEALFAKTRYPDIFMREEVALKIN LPESRVQVWFKNRRAKCR
H. medicinalis/LOX6 SRYQTLELEKEFHFNRYLNGRRRIEIAHSLG LTERQIKIWFQNRRMKWK
G. lamblia/Dtprd AIWQLDQLEVVFKTSHYPDVSSRESLARSLG LPESRVQVWFQNRRAKWR
N. musculus/Limb3b TAKQLETLKSAYNTSPKPARHVREQLSSETG LDMRVVQVWFQNRRAKEK
H. sapiens/SMADI YKDHMSVLKAYYAMNMEPNSDELLKISIAVG LPQEFVKEWFEQRKVYQY
E
hatch
L1
L2
L4
adult
0
10
14
16
18
20
22
24
40
50
hours
wildtype
dve-1(uf171)
wild type
dve-1(uf171)
iAChR::GFP localization (%)
dorsal only
dorsal and ventral
ventral only
10 hours
24 hours
dorsal
ventral
iAChR
F
pre-remodeling
post-remodeling
LEV-10::GFP D/V-1 fluorescence (a.u.)
wild type
dve-1(uf171)
NATF DD LEV-10
G
wild type
dve-1(uf171)
dorsal
ventral
SV iAChR L4 stage
iAChR Clusters / 25 µm
SV Clusters / 25 µm
ventral
dorsal

931 **Figure 1. Mutations in the homeodomain transcription factor DVE-1 disrupt the removal of**
932 **postsynaptic sites in GABAergic motor neurons**

933 (A) Top, schematic of *C. elegans* labeling DD GABAergic motor neurons (purple). Bottom,
934 schematic depicting motor circuit remodeling. Left, embryonic DD motor neurons (purple)
935 receive input from cholinergic motor neurons (blue) in the dorsal nerve cord and make
936 synaptic contacts onto ventral muscles. Right, after the L1-L2 molt, DD motor neurons are
937 remodeled to receive inputs from postembryonic born cholinergic motor neurons in the
938 ventral nerve cord and make synaptic contacts onto dorsal muscles.

939 (B) Fluorescent confocal images of synaptic ACR-12::GFP clusters (iAChRs, green) in
940 GABAergic DD processes of the dorsal nerve cord at L4 stage. By L4 stage, iAChR clusters
941 are completely eliminated from the dorsal nerve cord of wild type animals. In contrast,
942 iAChR clusters remain present in the dorsal nerve cord of *dve-1* mutants. Rescue refers to
943 expression of genomic sequence encoding wild type DVE-1. OE refers to overexpression
944 of *dve-1* in the wild type. In this and subsequent figures, iAChR refers to ACR-12::GFP
945 unless otherwise indicated. Scale bar, 5 μm.

946 (C) Quantification of iAChR clustering at L4 stage for the genotypes indicated. Left, bars
947 represent the percentage of L4 stage animals where dorsal iAChRs have been completely
948 removed. ****$p<0.0001$, Fischer's exact test with Bonferroni Correction. For this and
949 subsequent figures, numbers within bars indicate the number of animals scored for each
950 condition. Right, measures of average fluorescence intensity per 25 μm in the dorsal nerve
951 cord. Bars indicate mean ± SEM. **$p<0.05$, ****$p<0.0001$, ns – not significant ANOVA with
952 Dunnett's multiple comparisons test. Each point represents a single animal. The number
953 of animals >10 per genotype.

954 (D) Domain structure of DVE-1. SATB-like domain and homeodomains (HOX) are indicated.
955 Site of substitution produced by *uf171* missense mutation (red) and region of *tm4803*

956 deletion mutation (blue) are indicated. Inset, sequence alignment of homeodomain 1
957 (determined using NCBI Blast Conserved Domains).
958 (E) Top, timeline of remodeling, approximate timing of transitions between larval stages and
959 adulthood are indicated. Bars indicate duration of DD synaptic remodeling for wild type
960 (blue) and *dve-1* mutants (magenta). Elimination of dorsal cord iAChR clusters is
961 completed by 22 hours after hatch for wild type whereas dorsal iAChR clusters persist
962 through adulthood in *dve-1* mutants. Middle, quantification of iAChR remodeling in DD
963 neurons of wild type (left) and *dve-1* mutants (right). X-axis time from hatching in hours.
964 Animals are binned according to the distribution of iAChR puncta as dorsal only (white),
965 ventral only (black), or dorsal and ventral (grey). Bottom, representative images of dorsal
966 and ventral iAChR clusters for wild type (left) and *dve-1* mutants (right) at the times
967 indicated. *$p<0.05$, ** $p<0.01$, *** $p<0.001$, Fischer's exact test. Scale bar, 5 μm.
968 (F) Top, scatterplot of LEV-10::GFP dorsal/ventral fluorescence intensity ratio measurements
969 per corresponding 25 μm regions of dorsal and ventral nerve cord expressed as
970 dorsal/ventral fluorescence ratio -1. Values greater than zero indicate predominant dorsal
971 localization while values less than zero indicate predominant ventral localization. The
972 postsynaptic scaffold LEV-10::GFP is incompletely removed from dorsal nerve cord in *dve-*
973 *1(uf171)* mutants. Bars indicate mean ± SEM. ***$p<0.001$, ns – not significant student's t-
974 test. Bottom, confocal images of LEV-10::GFP from the dorsal nerve cord before (pre-
975 remodeling) and after (post-remodeling) the L1/L2 transition. Scale bar, 5 μm. NATF DD
976 LEV-10 indicates tissue-specific labeling of endogenous LEV-10 [30]. Each point
977 represents a single animal. The number of animals >10 per genotype.
978 (G) Top, confocal images of the dorsal and ventral process from L4 stage wild type and *dve-*
979 *1(uf171)* mutants co-expressing the synaptic vesicle marker mCherry::RAB-3 (SV) and
980 ACR-12::GFP marker (iAChR) in DD neurons. Scale bar, 5 μm. Bottom, quantification of
981 iAChR clusters (left) and SV puncta (right) in dorsal and ventral processes of L4 stage DD

982 neurons for wild type and *dve-1(uf171)* mutants. iAChRs in DD neurons are not eliminated
983 from the dorsal nerve cord of L4 stage *dve-1* mutants, but new clusters form normally in
984 the ventral nerve cord. SV clusters are properly reoriented from the ventral cord to the
985 dorsal nerve cord in DD neurons of *dve-1* mutants. Bars indicate mean ± SEM. Student's
986 t-test, ****$p<0.0001$, ns – not significant. Each point represents a single animal.

987 **Table 1. Mutations that delay GABAergic presynaptic remodeling do not affect cholinergic**

988 **postsynaptic remodeling in DD motor neurons**

AChR (*flp-13pr*::ACR-12::GFP)

genotype (L4 stage)	percent remodeled (ventral only) (n)	percent not remodeled (dorsal only + both sides)	total (n)	Fischer's Exact P-Value	Bonferroni correction (significant?) α <0.003
wild type	100 (93)	0 (0)	93		
ced-3(ok2734)[26]	100 (21)	0 (0)	21	1	no
ced-3(n717) [26]	100 (23)	0 (0)	23	1	no
cdk-5(ok626)[20]	100 (20)	0 (0)	20	1	no
unc-8(e49) [19]	100 (20)	0 (0)	20	1	no
unc-8(e15) [19]	100 (10)	0 (0)	10	1	no

SV *(flp-13pr*::mCherry::RAB-3)

genotype (L4 stage)	percent remodeled (dorsal only) (n)	percent not remodeled (ventral only + both sides)	total (n)	Fischer's Exact P-Value	Bonferroni correction (significant?) α <0.01
wild type	100 (30)	0 (0)	30		
ced-3(ok2734)[26]	56 (6)	44 (5)	11	0.0006	yes
ced-3(n717) [26]	57 (13)	43 (10)	23	0.0001	yes
cdk-5(ok626)[20]	36 (4)	64 (7)	11	0.0001	yes
unc-8(e49) [19]	56 (9)	44 (7)	16	0.0002	yes
unc-8(e15) [19]	60 (6)	40 (4)	10	0.0023	yes

989

990 **Table 2. Effects of synaptic activity and calcium signaling on synaptic remodeling**

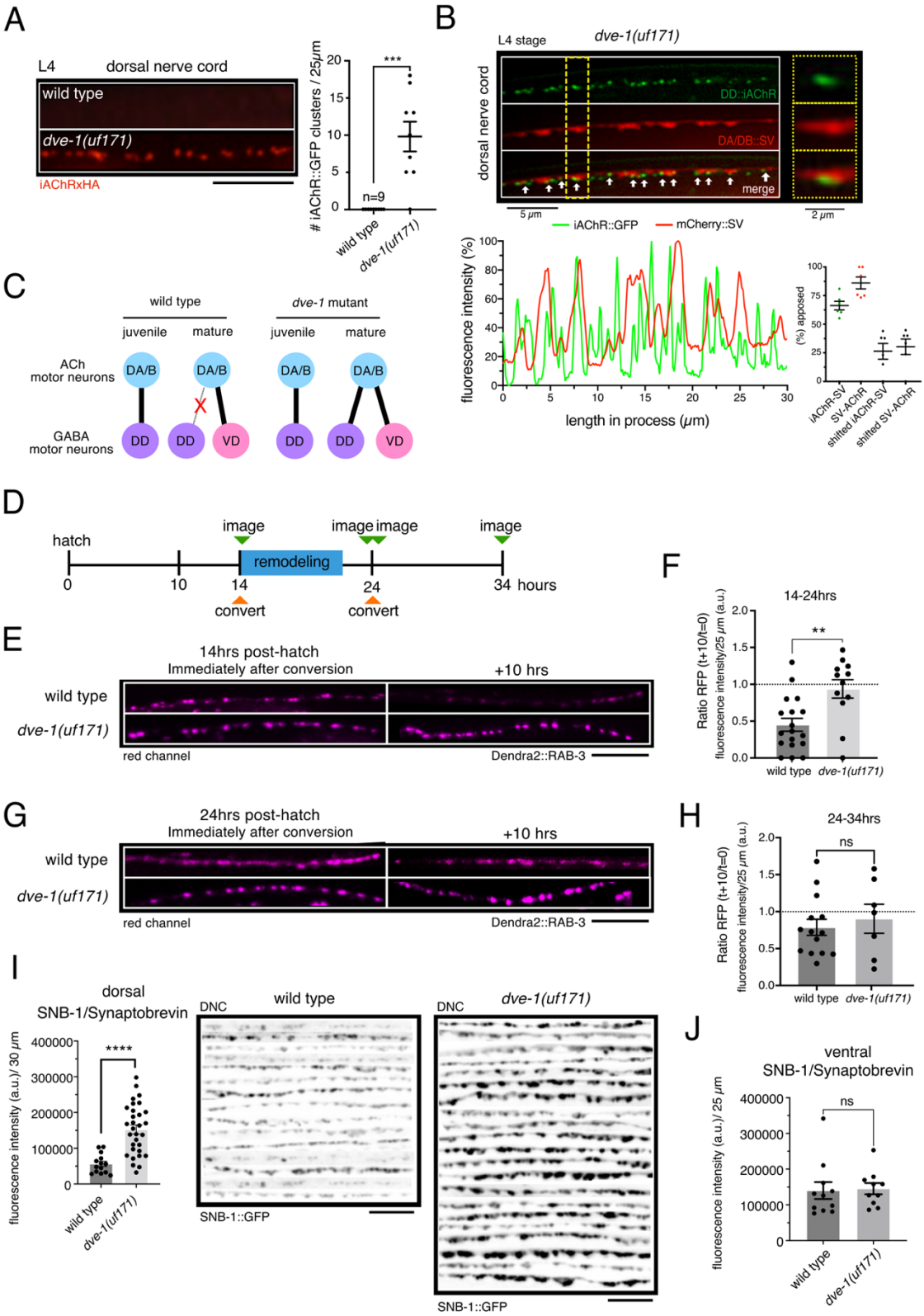
AChR (*flp-13pr*::ACR-12::GFP)

genotype (24hrs post-hatch)	percent remodeled (ventral only) (n)	percent not remodeled (dorsal only + both sides)	total (n)	Fischer's Exact P-Value	Bonferroni correction (significant?) α <0.0055
wild type	96 (64)	4 (3)	67		
unc-2(e55)[19]	100 (10)	0 (0)	10	1	no
cca-1(ad1650)	100 (17)	0 (0)	17	1	no
itr-1(sa73)	100 (18)	0 (0)	18	1	no
unc-68(e540)	50 (6)	50 (6)	12	0.0002	yes
unc-13(e51)	100 (11)	0 (0)	11	1	no
unc-43(e408)	95 (19)	5 (1)	20	1	no
unc-18(e234)[21]	100 (10)	0 (0)	10	1	no
unc-17(e113)	76 (13)	24 (4)	17	0.0284	no

genotype (L4 stage)	percent remodeled (ventral only) (n)	percent not remodeled (dorsal only + both sides)	total (n)	Fischer's Exact P-Value	Bonferroni correction (significant?) α <0.003
wild type	100 (93)	0 (0)	93		
unc-2(e55)[19]	100 (10)	0 (0)	10	1	no
unc-2(zf35)[19]	86 (6)	14 (1)	7	0.07	no
cca-1(ad1650)	100 (10)	0 (0)	10	1	no
itr-1(sa73)	100 (10)	0 (0)	10	1	no
unc-68(e540)	100 (11)	0 (0)	11	1	no
unc-43(e408)	100 (9)	0 (0)	9	1	no
unc-43 (n498)	100 (14)	0 (0)	14	1	no
unc-18(e234)[21]	100 (8)	0 (0)	8	1	no
unc-31 (e928)[21]	100 (10)	0 (0)	10	1	no
unc-17(e113)	100 (11)	0 (0)	11	1	no

SV (*flp-13pr*::mCherry::RAB-3)

genotype (24hrs post-hatch)	Percent remodeled (dorsal only) (n)	percent not remodeled (ventral only + both sides)	total (n)	Fischer's Exact P-Value	Bonferroni correction (significant?) α <0.025
wild type	97 (28)	3 (1)	29		
unc-18(e234)[21]	40 (4)	60 (6)	10	0.0004	yes
unc-17(e113)	33 (2)	67 (4)	6	0.0014	yes



991 **Figure 2. Mutation of *dve-1* enhances stability of cholinergic presynaptic sites**

992 (A) Left, fluorescent confocal images of L4 stage cell surface iAChR clusters in the dorsal nerve
993 cord labeled by anti-HA antibody fluorescence (red). Scale bar, 5 μm. Right, scatterplot of
994 average number of dorsal receptor clusters per 25 μm. Each point represents a single
995 animal n=9 for both genotypes. Data points represent mean ± SEM. ***p<0.001, students t-
996 test.
997 (B) Top, merged fluorescent confocal images of L4 stage *dve-1* mutant dorsal nerve cord
998 showing lingering clusters of juvenile postsynaptic iAChRs (*flp-13pr*::ACR-12::GFP, green)
999 in the DD neurons and synaptic vesicles (SV, *unc-129pr*::mCherry::RAB-3, red) in
1000 presynaptic cholinergic DA/DB neurons. Dashed yellow line indicates area shown in inset
1001 (right). Bottom, line scan (left) and quantification (right) indicating % apposition of
1002 postsynaptic iAChR and presynaptic cholinergic vesicle clusters. Line scan indicates relative
1003 fluorescence intensity of iAChR (green) and SV (red) for a 30 μm region of L4 stage *dve-1*
1004 mutant dorsal nerve cord. Scatterplot shows the percentage apposition between iAChR
1005 clusters in DD motor neurons and cholinergic synaptic vesicle puncta in DA/B motor neurons
1006 (green). As controls (black) each iAChR and SV line scan was shifted by 2 μm and
1007 reassessed to determine percent apposed by chance. Each point represents a single
1008 animal. The number of animals >5. Data points indicate mean ± SEM.
1009 (C) Simplified schematic of DA/B synaptic output. In the juvenile circuit (L1 stage) DA/B motor
1010 neurons (blue) synapse onto DD motor neurons (purple) in both wild type (left) and *dve-1*
1011 mutants (right). In the wild type mature circuit (L2 through adulthood) DA/B connections with
1012 DD motor neurons have been removed, and new connections with postembryonic born VD
1013 motor neurons (pink) are formed (left). Grey line with red “X” indicates removal of juvenile
1014 connection. Our findings suggest that connections between cholinergic DA/B neurons and
1015 DD neurons are retained in *dve-1* mutants retain (right).
1016 (D) Schematic of photoconversion experimental design. Animals were imaged 14 hours after
1017 hatch, prior to and immediately after photoconversion. Photoconverted animals were

1018 imaged again 10 hours later. Photoconversion was performed again 24 hours after hatch.
1019 Images were captured immediately after conversion and again 10 hours later (34 hours after
1020 hatch).

1021 (E) Confocal images of the dorsal nerve cord of wild type (top) and *dve-1(uf171)* mutants
1022 (bottom) showing red Dendra2::RAB-3 clusters in cholinergic DA/B neurons (*unc-*
1023 *129pr*::Dendra2::RAB-3) either immediately after photoconversion from green to red at 14
1024 hours after hatch (left) or 10 hours later (right). Juvenile Dendra2::RAB-3 clusters are largely
1025 removed during wild type remodeling but are more stable in *dve-1* mutants. Scale bar, 5 µm.

1026 (F) Scatterplot showing red Dendra2::RAB-3 fluorescence intensity 10 hours after
1027 photoconversion normalized to fluorescence intensity immediately after photoconversion
1028 prior to remodeling for wild type (left) and *dve-1(uf171)* mutants (right). Each point indicates
1029 a single animal. The number of animals >10 per genotype. Bars indicate mean ± SEM.
1030 ***p*<0.01, student's t-test.

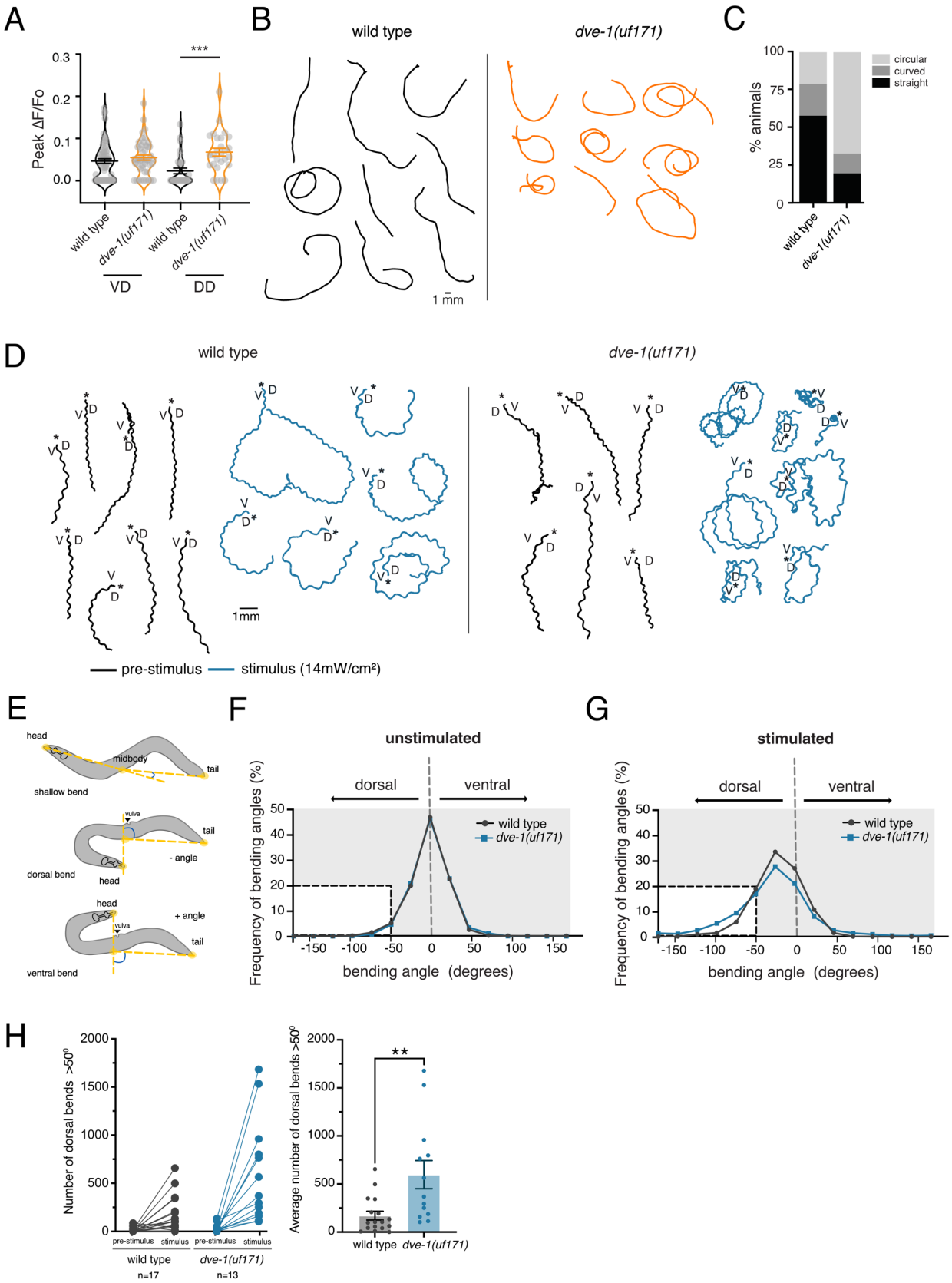
1031 (G) Confocal images of the dorsal nerve cord of wild type (top) and *dve-1(uf171)* mutants
1032 (bottom) showing red Dendra2::RAB-3 clusters in cholinergic DA/B neurons either
1033 immediately after photoconversion from green to red at 24 hours after hatch (left) or 10
1034 hours later (right). For both wild type and *dve-1* mutants, photoconverted cholinergic
1035 Dendra2::RAB-3 clusters are more stable following remodeling compared with during
1036 remodeling. Scale bar, 5 µm.

1037 (H) Scatterplot showing red Dendra2::RAB-3 fluorescence intensity 10 hours following
1038 photoconversion normalized to fluorescence intensity immediately after photoconversion at
1039 24 hours after hatch (after remodeling) for wild type (left) and *dve-1(uf171)* mutants (right).
1040 Each point indicates a single animal. The number of animals >6 per genotype. Bars indicate
1041 mean ± SEM. ns - not significant, student's t-test.

1042 (I) Left, scatterplot showing average SNB-1::GFP fluorescence intensity in L4 stage cholinergic
1043 neurons (*acr-5pr*::SNB-1::GFP) of the dorsal nerve cord (DNC) for wild type and *dve-1*

1044 mutants. Each point indicates a single animal. The number of animals >10 per genotype.
1045 Bars indicate mean ± SEM. ****p< 0.0001, student's t-test. Right, stacked fluorescent
1046 images of the dorsal nerve cord showing SNB-1::GFP clusters in cholinergic neurons of L4
1047 stage wild type and *dve-1(uf171)* mutants. Images on each line are from different animals.
1048 Scale bar, 5 µm.

1049 (J) Scatterplot of average synaptic vesicle puncta (SNB-1::GFP) per 30 µm in the ventral nerve
1050 cord of VB motor neurons of L4 stage wild type and *dve-1* mutant animals. Each point
1051 represents a single animal. At least 10 animals per genotype. Bars indicate mean ± SEM.
1052 ns - not significant, student's t-test.



1053 **Figure 3. Failure of synapse elimination in *dve-1* mutants produces dorsal turning bias**

1054 (A) Scatter plot showing peak calcium response ($\Delta F/F_0$) in DD and VD GABAergic neurons to
1055 photostimulation of presynaptic DA and DB cholinergic neurons for wild type and *dve-1(uf171)*
1056 mutants. Horizontal bars indicate mean peak $\Delta F/F_0$ ± SEM. *** $p<0.001$, ANOVA with Tukey's
1057 multiple comparison. n=16; animals for each condition. Number of cells quantified: wt DD: 30,
1058 *dve-1(uf171)* DD: 27, wt VD: 64, *dve-1(uf171)* VD: 47.
1059 (B) Representative locomotion tracks for wild type (black) and *dve-1(uf171)* (orange) animals
1060 recorded over 5 minutes of single worm tracking on NGM OP50 plates. Scale bar, 1 mm.
1061 (C) Percentage of straight, curved, or circling tracks for wild type and *dve-1(uf171)* mutants.
1062 (D) Tracks for wild type (left) and *dve-1* mutant (right) animals during forward runs (30 s) prior to
1063 or during photostimulation. Asterisks indicate start of track. D/V indicate dorsal and ventral
1064 directions.
1065 (E) Schematics of bending angle measurements. Solid orange circles indicate the vertices (head,
1066 midbody, and tail) of the body bending angle (blue) measured.
1067 (F) Frequency distribution of body bending angles measured prior to photosimulation for wild type
1068 (black) and *dve-1(uf171)* (blue). Negative bending angle values indicate dorsal, while positive
1069 bending angle values indicate ventral. Inset highlights bending events greater than 50°. wild
1070 type n=17, *dve-1(uf171)* n=13.
1071 (G) Frequency distribution of body bending angles measured during photostimulation for wild type
1072 (black) and *dve-1(uf171)* (blue). Negative bending angle values indicate dorsal, while positive
1073 bending angle values indicate ventral. Inset highlights bending events greater than 50°. wild
1074 type n=17, *dve-1(uf171)* n=13.
1075 (H) Left, scatterplot of total number of dorsal bends greater than 50° before and after
1076 photostimulation. Points with connecting line represents a single animal. Right, average
1077 number of dorsal bends greater than 50° during the period of photostimulation for wild type
1078 and *dve-1(uf171)* animals. Bars indicate mean ± SEM. ** $p<0.01$, student's t-test. wild type
1079 n=17, *dve-1(uf171)* n=13.

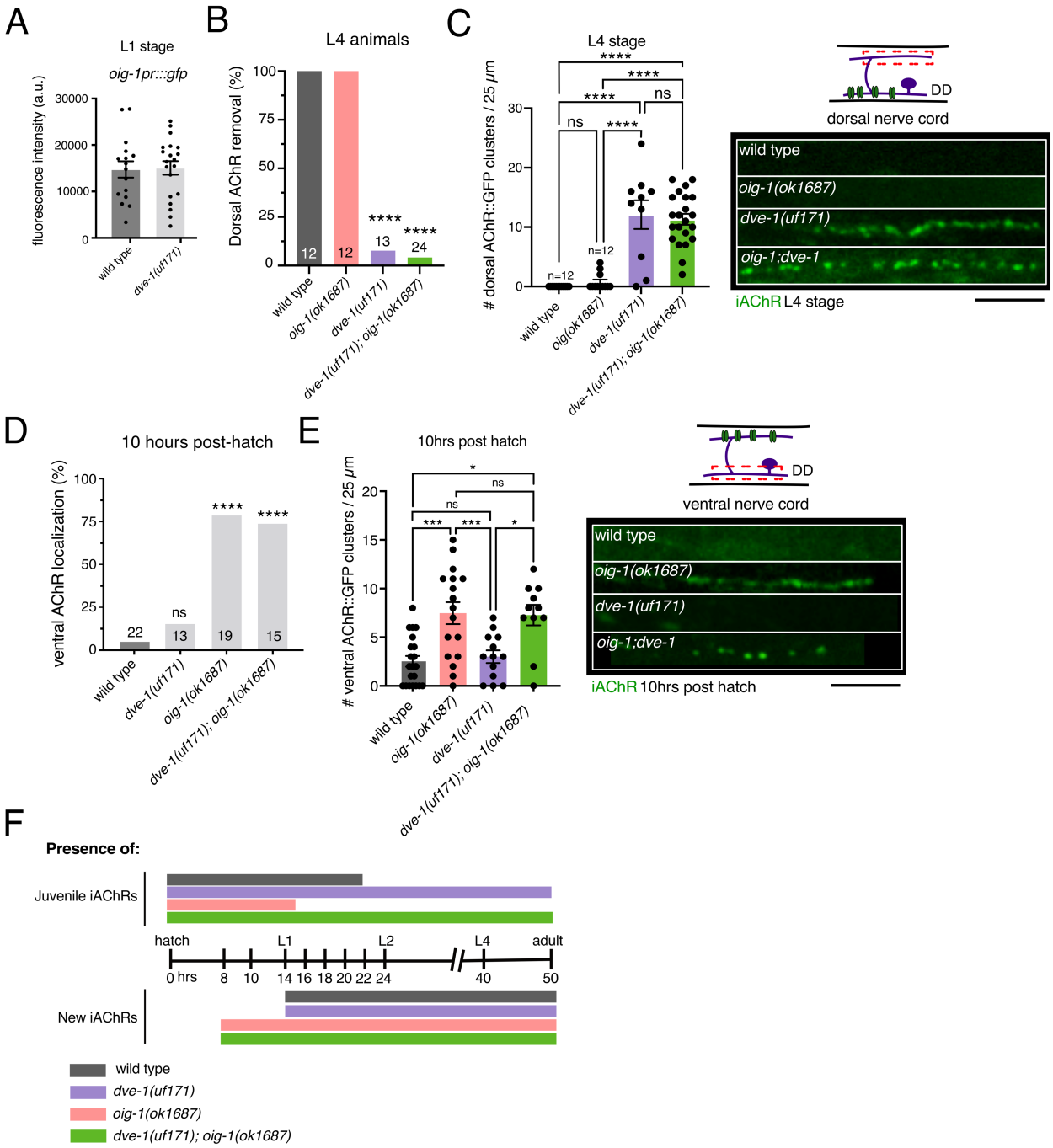


Figure 4. *dve-1* synaptic destabilization acts in parallel to *oig-1* antagonism of remodeling

(A) Average fluorescence intensity of *oig-1pr::gfp* in DD soma of L1 stage wild type and *dve-1* mutants. Each point represents a single DD cell body. Imaged 2 DD neurons/animal. Wild type n=8, *dve-1* mutants n=10. Bars indicate mean ± SEM.

1084 (B) The percentage of animals where dorsal iAChRs are eliminated for L4 stage wild type,
1085 *oig-1(ok1687)*, *dve-1(uf171)* and *dve-1(uf171);oig-1(ok1687)* double mutants. ****$p<$
1086 0.0001, Fischer's exact test with Bonferroni Correction.
1087 (C) Left, quantification of average number of iAChR clusters in L4 stage DD neurons per 25
1088 μm of the dorsal nerve cord for the genotypes indicated. Each dot represents a single
1089 animal, at least 10 animals per genotype. Bars indicate mean ± SEM. ****$p<0.0001$, ns -
1090 not significant, ANOVA with Dunnett's multiple comparisons test. Right, fluorescent
1091 confocal images of iAChR clusters in L4 stage DD neurons of the dorsal nerve cord for
1092 the genotypes indicated. The precocious removal of dorsal iAChRs in *oig-1* mutants is
1093 reversed by mutation of *dve-1*. iAChR clusters persist through L4 stage in in both *dve-1*
1094 single and *oig-1;dve-1* double mutants. Scale bar, 5 μm.
1095 (D) Quantification of iAChR ventral localization in DD neurons in wild type, *oig-1(ok1687)*
1096 mutant, *dve-1(uf171)* mutant and *dve-1(uf171), oig-1(ok1687)* double mutant L1 stage
1097 animals (10 hours). ****$p<0.0001$, ns-not significant, Fischer's exact test.
1098 (E) Left, quantification of average number of iAChR clusters in DD neurons per 25 μm of the
1099 ventral nerve cord at L1 stage for the genotypes indicated. Each dot represents a single
1100 animal, at least 10 animals per genotype. Bars indicate mean ± SEM. ANOVA with
1101 Dunnett's multiple comparisons test, *$p<0.05$, ***$p<0.001$, ns-not significant. Right,
1102 fluorescent confocal images of iAChR clusters in the ventral processes of L1 stage DD
1103 neurons. Growth of ventral iAChR cluster occurs precociously in *oig-1* mutants and is
1104 unaffected by *dve-1* mutation. Scale bar, 5 μm.
1105 (F) Timeline of development, approximate timing of transitions between larval stages and to
1106 adulthood are indicated. Bars indicate the presence of juvenile dorsal iAChRs (top) or
1107 ventral iAChRs formed during remodeling (bottom). *dve-1* mutants (magenta) fail to
1108 remove juvenile synapses but form ventral synapses normally. *oig-1* mutants (orange)
1109 show precocious removal of juvenile synapses and precocious formation of ventral

1110 synapses compared to wild type (blue). *oig-1;dve-1* double mutants (green) fail to remove
1111 juvenile synapses similar to *dve-1* single mutants, but show precocious formation of new
1112 ventral synapses similar to *oig-1* single mutants.

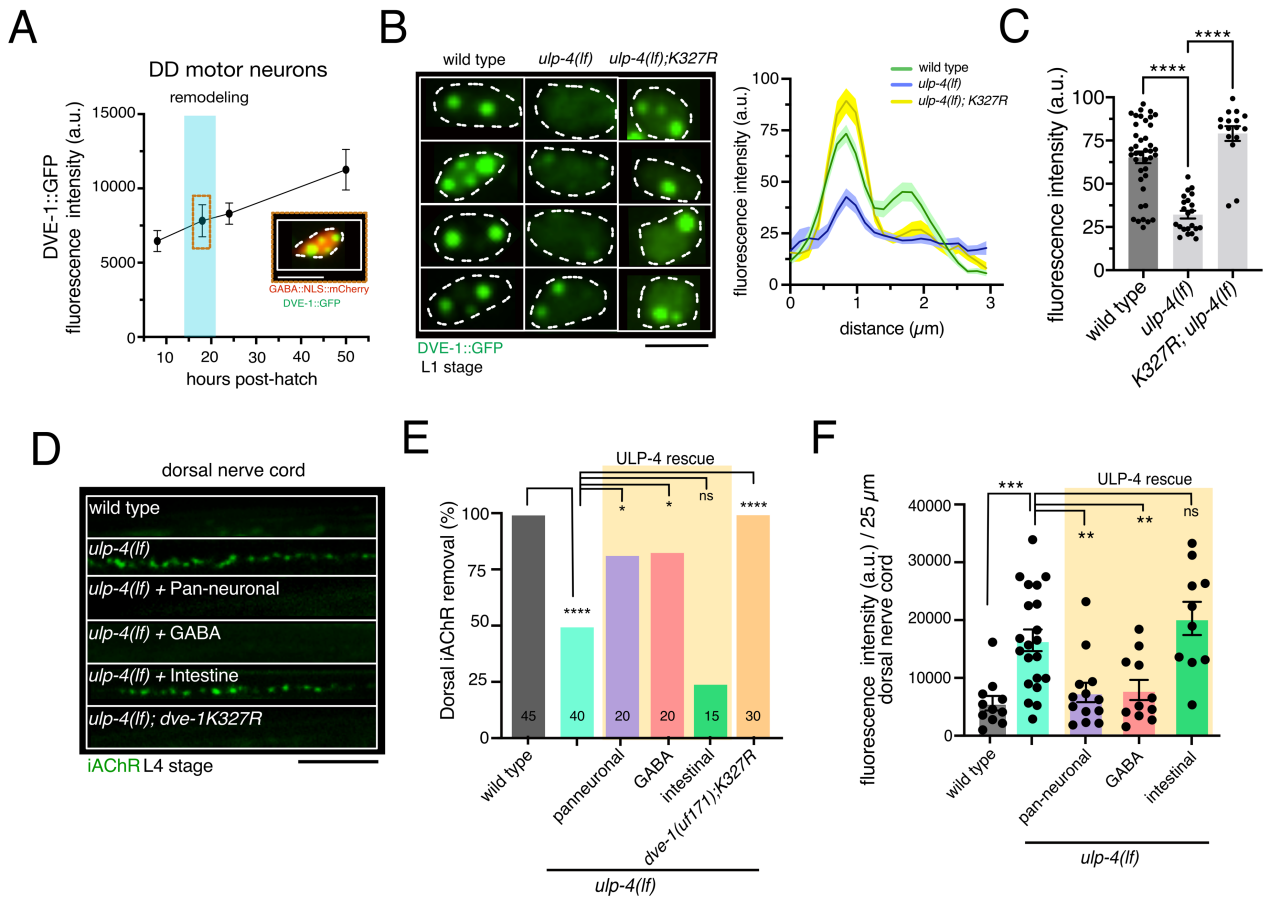


Figure 5. DeSUMOylating peptidase ULP-4 regulates nuclear localization of DVE-1

(A) Fluorescence intensity of nuclear DVE-1::GFP in DD motor neurons at 10, 18, 22 and 50 hours after hatch. Nuclear DVE-1::GFP is organized in discrete foci and increases through development. Each time point indicates mean ± SEM from at least three independent experiments. Inset, representative image of nuclear DVE-1::GFP in DD motor neuron 18 hours after hatch (nucleus labeled by NLS::mCherry). White dashed line outlines nucleus. Scale bar, 3 μm.

(B) Confocal fluorescence images (left) of DVE-1::GFP in DD GABAergic motor neurons of L1 stage wild type, *ulp-4(lf)* mutant, and *K327R;ulp-4(lf)* double mutants. *ulp-4(lf)* disrupts DVE-1::GFP nuclear localization. DVE-1(K327R) disrupts SUMOylation of DVE-1 and restores DVE-1::GFP nuclear localization in *ulp-4(lf)*. White dashed line outlines nucleus. Scale bar, 3 μm. Right, line scan of nuclear DVE-1::GFP fluorescence intensity in DD motor neurons

1125 of wild type (green) n=16, *ulp-4(lf)* (blue) n=11 and DVE-1(K327R)*;ulp-4(lf)* double mutants
1126 (yellow) n=8. Solid line represents mean, shading represents standard deviation of
1127 fluorescence.

1128 (C) Scatterplot (left) of the peak nuclear DVE-1::GFP fluorescence intensity in DD motor
1129 neurons. Each point represents a single DD nucleus. Imaged at least 2 DD cells per animal
1130 at L1 stage. Wild type: n=16, *ulp-4(lf)*: n=11, *K327R;ulp-4(lf)*: n=8. Bars indicate mean ±
1131 SEM. ****p<0.0001, ANOVA with Dunnett's multiple comparisons test.

1132 (D) Fluorescent confocal images of iAChR clusters in the dorsal processes of L4 stage DD
1133 neurons. iAChRs remained present in the dorsal nerve cord of L4 stage *ulp-4(lf)* mutants,
1134 indicating a failure in juvenile synapse elimination. Either pan-neuronal or specific
1135 expression of wild type *ulp-4* cDNA in GABAergic neurons was sufficient to restore synapse
1136 elimination. Scale bar, 5 μm.

1137 (E) Quantification of iAChR clustering at L4 stage for the genotypes indicated. Bars indicate the
1138 percentage of L4 stage animals where dorsal iAChRs have been completely removed.
1139 *p<0.05, ****p<0.0001, ns – not significant, Fischer's exact test with Bonferroni correction.
1140 1/2 pan-neuronal lines, 2/2 GABA lines, and 0/2 intestinal rescue lines restored proper
1141 removal of dorsal iAChRs by L4.

1142 (F) Scatterplot of average iAChR fluorescence intensity/25 μm in the dorsal nerve cord at L4
1143 stage for the genotypes indicated. Each point represents a single animal. Bars indicate
1144 mean ± SEM. **p<0.05, ***p<0.001, ns – not significant, ANOVA with Dunnett's multiple
1145 comparisons test. The number of animals was >10 per genotype.

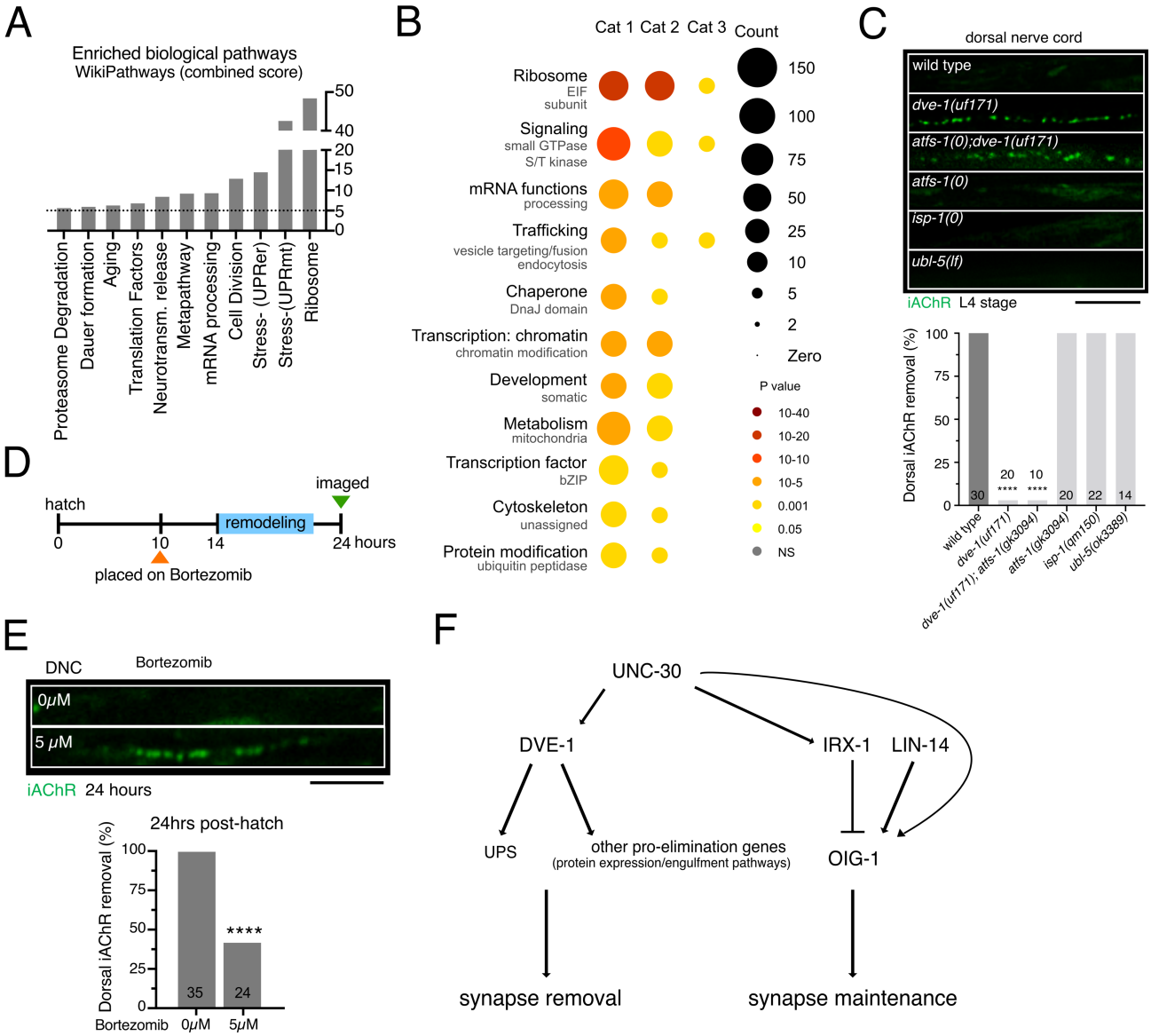


Figure 6. Enrichment analysis of DVE-1 ChIP-seq targets reveals potential pathways governing synapse elimination

(A) The WormEnrichR pathway enrichment analysis utilizing both the Kyoto Encyclopedia of Genes and Genomes (KEGG) database and the WikiPathway database. Bars represent enriched pathways with a combined score >10 (dashed line) and p-adj < 0.05. Y-axis is segmented between 40-60.

1152 (B) Wormcat analysis for significantly enriched categories of putative DVE-1 targets identified
1153 from ChIP-seq dataset. size of circles indicates the number of genes and color indicates
1154 the value of significant over-representation in each Wormcat category.
1155 (C) Induction or inhibition of mtUPR has no effect on synapse elimination. Top, fluorescent
1156 confocal images of iAChR clusters in the dorsal processes of DD neurons at L4 stage.
1157 Scale bar, 5 μm. Bottom, bars indicate the percentage of L4 stage animals that have
1158 eliminated dorsal iAChRs. ****$p < 0.0001$, Fischer's exact test with Bonferroni correction.
1159 (D) Schematic of Bortezomib inhibitor experimental design. Animals were placed on
1160 Bortezomib plates at 10 hours after hatch. animals were allowed to grow on this inhibitor
1161 until imaging at 24 hours after hatch.
1162 (E) Top, fluorescent confocal images of iAChR clusters in the dorsal processes of DD neurons
1163 at 24 hours post-hatch grown on (5μM) or off (0μM) Bortezomib inhibitor plates. Bottom,
1164 bars indicate the percentage of animals that have removed dorsal iAChRs by 24 hours
1165 post-hatch. ****$p < 0.0001$, Fischer's exact test.
1166 (F) Transcriptional control of DD remodeling. The GABAergic terminal selector transcription
1167 factor UNC-30/Pitx regulates the cellular expression of both *dve-1* and *oig-1* [23, 24], this
1168 paper. *oig-1* encodes an Ig-domain protein that stabilizes juvenile synapses prior to
1169 remodeling. Temporal control of *oig-1* expression is encoded through additional
1170 transcriptional regulation by LIN-14 and IRX-1 transcription factors [23, 24]. We show that
1171 DVE-1 promotes synapse removal/destabilization, perhaps through transcriptional
1172 regulation of the ubiquitin proteasome system (UPS). Mutation of *dve-1* impairs synapse
1173 removal, even when OIG-1 mediated stabilization is removed.

1174 **Table 3: Potential ubiquitin proteasome system targets of DVE-1 revealed by ChIP-**

1175 **seq analysis**

C. elegans	*H. sapiens*	Gene Description	Enrichment tool
		Proteasome subunit/composition	
pas-5	PSMA5	proteasome subunit alpha 5 (20S proteasome)	WormCat, WikiPathways (wormenrichr)
rpt-5	PSMC3	proteasome 26S subunit ATPase 3 (26S proteasome)	WormCat, WikiPathways (wormenrichr)
rpt-6	PSMC5	proteasome 26S subunit ATPase 5 (26S proteasome)	WormCat, WikiPathways (wormenrichr)
		Ubiquitin	
ubq-1	UBC	Ubiquitin, polyubiquitin locus	WormCat, WikiPathways (wormenrichr)
		E2 Enyzme	
ubc-2/let-70	UBE2D1/UBE2D2/UBE2D3	E2 ubiquitin conjugating enzyme	WormCat, WikiPathways (wormenrichr)
		E3 Enzyme HECT-Domain	
wwp-1	ITCH	HECT-domain ubiquitin E3 ligase	WormCat
eel-1	HUWE1	HECT-domain ubiquitin E3 ligase	WormCat
		E3 Enzyme RING-finger complex	
cul-5	CUL5	RING finger complexe cullin 5	WormCat
rfp-1	RNF20	ring finger protein 20	WormCat
C11H1.3	MGRN1	mahogunin ring finger 1	WormCat
rnf-113	RNF113A	ring finger protein 113A	WormCat
spat-3	RING1/RING2	ring finger protein 1/2	WormCat
		DUB Enzymes	
usp-48	USP48	Ubiquitin-Specific Protease 48	WormCat
usp-14	USP14	Ubiquitin-Specific Protease 14	WormCat
otub-1	OTUB1/2	otubain-1/2	WormCat
H34C03.2	USP11	Ubiquitin Specific Peptidase 11	WormCat
T22F3.2	USP17L1	Ubiquitin Specific Peptidase 17 Like Family Member 1	WormCat
otub-2	OTUD7A	OTU Deubiquitinase 7A	WormCat
		UPS associated	
C46F11.6	UBL3	Ubiquitin-like 3	WormCat
wdr-23	DCAF11/WRD23	DDB1 And CUL4 Associated Factor 11	WormCat
ubql-1	UBQLN4	ubiquilin 4	WormCat
atg-7	ATG7	autophagy related	WormCat
ppm-2	PPM1A	protein phosphatase, Mg2+/Mn2+dependent 1A	WormCat
K02A6.3		F-box domain	WormCat
spsb-1	SPSB1	a Spry domain-containing Socs box protein	WormCat
cpi-2	CST3/6	cysatin C/cystatin E/M	WormCat
try-6	TMPRSS13	transmembrane serine protease 13	WormCat
spcs-3	SPCS3	signal peptidase complex subunit 3	WormCat