Title: Developmental and age-related synapse elimination is mediated by glial Croquemort

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Summary:

Neurons and glia work together to dynamically regulate neural circuit assembly and maintenance. In this study, we show *Drosophila* exhibit large-scale synapse formation and elimination as part of normal CNS circuit maturation, and that glia use conserved molecules to regulate these processes. Using a high throughput ELISA-based *in vivo* screening assay, we identify new glial genes that regulate synapse numbers in *Drosophila in vivo,* including the scavenger receptor ortholog Croquemort (Crq). Crq acts as an essential regulator of glial-dependent synapse elimination during development, with glial Crq loss leading to excess CNS synapses and progressive seizure susceptibility in adults. Loss of Crq in glia also prevents age-related synaptic loss in the adult brain. This work provides new insights into the cellular and molecular mechanisms that underlie synapse development and maintenance across the lifespan, and identifies glial Crq as a key regulator of these processes.

Keywords:

Glia, astrocyte, neurodevelopment, synaptogenesis, neuronal remodeling, Crq, SCARB2, CD36, synaptic pathologies, seizure

Introduction:

Establishing and maintaining appropriate synaptic connections is critical for nervous system function. During development, synapse formation and selective synapse elimination act together to construct this precise synaptic circuitry. Disruption in the process of synapse formation has been implicated in intellectual disability[1], injury-induced pain[2], and failure to recover after stroke[3]. Disruption in synapse elimination is associated with epilepsy[4], autism[5] and schizophrenia[6], and aberrant elimination of synapses leads to cognitive decline with aging[7] and in neurodegenerative diseases[8]. Understanding mechanisms that contribute to the formation and elimination of synapses will therefore be critical to understand normal development and neurological disease.

Over the past two decades, we have come to appreciate that neurons do not orchestrate synapse development alone. Glia are essential regulators of both synapse formation and elimination in development and disease[9,10]. For example, glial *TSP1/2*[11] and *SPARC*[12] were found to be required for excitatory synapse formation and maturation, and *MEGF10*[13] and complement[14,15] are necessary for synapse elimination and circuit refinement. Many of these molecules were initially found by growing subsets of neurons *in vitro,* with or without glia conditioned media, to identify secreted glial factors that regulate synapse development[16]. Others were found using targeted approaches, identifying candidates via screens in model organisms, transcriptional profiling or disease association studies, and then validating the role for these genes in synapse development using mouse models[13,15,17].

These studies have allowed us to learn primarily about the secreted molecules that glia employ to regulate development of synapses in excitatory neurons. However, contact-dependent mechanisms also play a role, though the molecular basis remains poorly defined[18,19]. Recent work demonstrates that glia also regulate inhibitory synapse development, though how glia regulate non-excitatory synapses remains relatively understudied[20,21]. Finally, it is important to note that *in vitro* systems cannot recapitulate endogenous patterns of cellular interactions, neuronal activity and biological age. We are therefore far from having a complete picture of neuron-glia signaling during establishment of circuit connectivity, and many *in vivo* synaptic regulatory molecules await discovery.

Addressing these questions will require large-scale gene discovery efforts in an *in vivo* system, and manipulation of gene expression in glia or neurons while reading out the effect on synapses. In this study, we use *Drosophila* for such a functional screen and provide evidence that *Drosophila* exhibit continued synapse formation and selective elimination throughout early adulthood, akin to the processes that occur during circuit maturation in mammals, as well as age-related synaptic loss. We identify 48 new genes that are required in glia *in vivo* for proper synapse development, including Crq, a scavenger receptor ortholog and part of an immune receptor family not previously implicated in synapse development. Loss of Crq in glia was sufficient to suppress glial synapse engulfment, resulting in increased synapse number and ultimately seizure susceptibility. Intriguingly, loss of Crq was sufficient to prevent age-related synaptic loss, in contrast to the well-studied engulfment receptor Draper (Drpr) / MEGF10, arguing for selective use of glial engulfment receptors during synapse loss in the aging brain.

Results:

***Drosophila* use conserved glial mechanisms to regulate synapse development and maintenance across the lifespan**

Formation of synapses that comprise the circuitry of adult *Drosophila* begins at late pupal stages[22]. We defined the dynamics of synaptic changes in *Drosophila* across their adult lifespan, and determine whether glia regulate synapse numbers (Fig 1A). As a proxy for measuring synapses, we evaluated levels of Brunchpilot (Brp), a molecule present in presynaptic active zones[23], and the canonical synaptic marker in the fly. We used an existing fly line in which Brp is endogenously tagged with GFP (Fig 1B) and measured GFP concentration in whole adult heads by ELISA[24]. Based on this assay, we found that, like mammals, adult flies appear to undergo defined periods of synapse formation and elimination during early adulthood (Fig 1C), with increases in Brp-GFP levels evident between eclosion (0 days post-eclosion – dpe) and early adulthood at 3 dpe, and a decrease observed between 3 dpe and mid-adulthood (10-12 dpe). *Drosophila* also exhibit synaptic loss in aged 30-35 dpe flies (Fig 1C). Thus, flies display very similar dynamics in synaptic marker levels across the lifespan as mice and humans.

We next sought to determine whether glia play a role in regulating these dynamic changes in synapses across the *Drosophila* lifespan. Glia have been previously implicated in regulating synapse formation in the fly, as partial ablation of astrocytes during development resulted in reduced synapse numbers[22]. To assess whether glia might also regulate developmental synapse elimination, we evaluated whether and when glia engage in phagocytic activity across late pupal through adult stages. Using genetically encoded markers in astrocytes, we observed FYVE-GFP, a PI3P marker which labels endosomes and has previously been used to monitor engulfment in the fly[25] (Fig 1D, E) and spn-RFP, a phagolysosomal marker (Fig 1F, G). This signal was present broadly across the brain at late pupal stages, and was maintained within 1 day of eclosion (0 dpe). These phagocytic markers were reduced at 3 dpe and decreased substantially by 10-12 dpe. These data are consistent with the notion that glia are actively phagocytic at times when synapse elimination occurs.

To more directly monitor synaptic engulfment, we adapted a transgene which had previously been used to evaluate synaptic engulfment in mammalian astrocytes[26] and generated a fly in which Brp was endogenously dual-labeled with a pH-insensitive mCherry and a pH-sensitive eGFP (Fig 1H). Using this tool, synapses appear dual labeled until they are engulfed and trafficked to acidic lysosomes, where the eGFP signal was quenched and only mCherry fluorescence remained. We quantified the number of mCherry^{+} eGFP- puncta from late pupal through early adult stages (Fig 1I). Engulfed synaptic material was present at late pupal stages, and this increased over the course of early adulthood, peaking at 3 dpe before dropping dramatically at 10-12 dpe (Fig 1J). We were able to visualize these puncta within astrocyte membranes (Fig S1A. Together, these data support the notion that *Drosophila* glia engulf synapses during early adulthood, coincident with a period of synapse elimination.

We next evaluated whether fly glia use similar molecular pathways to regulate synapse numbers in comparison to astrocytes in mammals. We first analyzed a TRAPseq dataset we generated[27] to assess changes in astrocyte gene translation across the developmental time points we identified as important periods of synapse formation and elimination (Fig S1B, Fig 1K). We found that orthologs to genes associated with synapse formation, *tsp* (*TSP1/2)*[11] and *sparc* (*Sparc / Hevin)*[12], and synapse elimination, *drpr* (*Megf10)*[13], were expressed in astrocytes during the developmental times when these processes occur in the fly (Fig 1L). We knocked each of these genes down in glia and measured the effects on levels of the synaptic protein Brp and found glial knockdown of *tsp* and *sparc* resulted in a reduction in synaptic protein levels, while knockdown of *drpr* resulted in an increase (Fig 1M).

While the strongest changes in the astrocyte translatome were present between late pupal stages and after eclosion (Fig S1C), there were still many genes that were differentially translated in astrocytes at early adulthood (1-3 dpe) compared to those at mid-adulthood (10-12 dpe) (Fig S1D). We also identified changes in gene expression in astrocytes after aging animals 50-60 days (Fig S1E, also see Table S1). This dataset provides a rich database to define mechanisms underlying changes in astrocyte phenotype across the lifespan. Moreover, our data argue that *Drosophila* glia exhibit conserved expression and function of previously established mammalian glial regulators of synapse development, and flies should therefore by a useful system in which to identify new glial regulators of synapse numbers.

An *in vivo* genetic screen identifies glial regulators of synapse development

We used available transcriptional and proteomic datasets to identify genes and proteins expressed in mammalian glia,[28-43] identified the fly orthologs of those genes, and screened them for roles in synapse formation or elimination *in vivo*. For each candidate, identified up to two RNAi lines available in public repositories[44] that would allow us to knockdown those genes, resulting in 695 genes and 971 screening lines (Table S2).

We took advantage of a screening paradigm we recently developed, using ELISA-based measurement of GFP levels in fly lysates to quantitatively measure levels of endogenously GFP-tagged proteins[24]. Specifically, we used this ELISA method to measure levels of the endogenously tagged synaptic protein, Brp-GFP as a proxy to evaluate synapses (Fig 2A). We found that we could reliably measure Brp-GFP signal from as little as ¼ of a fly head (Fig S2A, B). To minimize variability, we used male flies (Fig S2C), pooled 3 fly heads per sample and ran 3 biological replicates per line (Fig S2D). It had been previously reported that there are circadian changes in synapse levels in flies, as measured by Brp protein levels[45]. We found similar results for flies at 10-12 dpe and these changes were abrogated in *per*^{01} mutants in which circadian rhythms are disrupted[46] (Fig S2E). We did not observe significant circadian changes in synapses earlier in development, at 3 dpe (Fig S2F). Therefore, we chose to perform the screen at 3 dpe as it appeared to be an ideal time point to capture genes that affected dynamics of both synapse formation and elimination, and to avoid the potential confounding effect of circadian synaptic changes.

We then used our collection of RNAi lines to knockdown each of the selected genes, one at a time, specifically in glia using the *repo-Gal4* driver and evaluated Brp-GFP levels by ELISA (Fig 1B). Of the genes tested, 45 resulted in lethality when knocked out in glia (Fig S2G) and Brp-GFP levels were assessed in the remaining 926 lines (Fig 2B). In total, we found 48 genes that, when knocked down in glia, resulted in a 25% or greater change in Brp-GFP levels with a significance value cut-off of $p<0.01$, and an additional 135 that resulted in >15% changes with $p<0.05$ (Fig 2C).

To gain insight into the general categories of genes involved in glial regulation of synapse development, we performed gene ontology analysis on all of the genes identified in the screen that, when knocked down, resulted in a >15% increase (Fig 2D, E, 2SI) or decrease (Fig 2F, G, 2SJ) in Brp-GFP levels. Both included networks of genes involved in regulation of synapses or neuronal development in mammals, though in many of these cases, glia had not been previously implicated in the action of these genetic pathways. Among those genes whose loss increased Brp-GFP levels, enriched pathways included cell adhesion and ECM regulatory molecules, immune molecules and other signaling pathways (Fig 2D, E, 2SI). Those genes that, when knocked down, decreased Brp-GFP levels were enriched in several metabolic and catabolic processes (Fig 2F, G, 2SJ). Importantly, some of the categories molecules identified, such as neurotransmitter receptors, could only have been identified in an *in vivo* screen,

where glia maintain their endogenous interactions with neurons and those neurons are engaging in normal patterns of activity. Altogether, the results of this screen demonstrate the breadth of molecular pathways glia use to regulate synapse development, and provide molecular footholds to start dissecting these mechanisms.

Loss of glial Crq increases synapse numbers in development

Previous studies have identified immune-related molecules – complement proteins[15], chemokines[35] and other immune receptors[17] – as important regulators of synapse development in mammals. In line with this previous work, the most enriched pathway among the negative regulators of synapse development was pattern recognition receptors, part of a large network of pathways related to immune function. Specifically, we identified a class of immune molecules – scavenger receptors – six of which resulted in altered synaptic protein levels during development. To begin to explore the role that scavenger receptors might play in synapse development, we chose to focus on one of these, Croquemort (Crq), which also produced highly consistent results in our secondary screening. This two-pass transmembrane receptor is orthologous to two mammalian scavenger receptors, *CD36* and *SCARB2*. *SCARB2* mutations are the genetic cause of a rare, progressive form of epilepsy[47], demonstrating that this gene is somehow important for regulating circuit development, though the cause of this phenotype is unknown. Furthermore, both *SCARB2* and *CD36* variants have been associated with other diseases characterized by pathological synaptic changes, including autism[48], Alzheimer's disease[49,50] and Parkinson's disease[51,52]. These genetic associations suggest that Crq may have a conserved role in regulating synaptic circuits, and thus we chose to move forward with validating and understanding the function of glial Crq in synapse development.

Because the screen was based on measuring levels of a synaptic molecule, using an ELISA-based measurement of the synaptic protein Brp, we first wanted to validate these findings using orthogonal methods for measuring synapses, and additional genetic targeting strategies to manipulate Crq expression. Two RNAi lines in the screen that targeted *crq* resulted in an increase in Brp-GFP levels. Two additional RNAi lines were available from public repositories, and we found that knockdown of *crq* using any of these four RNAi lines resulted in a significant increase in Brp-GFP levels (Fig 3A). As with knockdown of *crq* in glia, we found that *crq* mutants exhibited significant and substantial increases in Brp protein levels by Western blot (Fig 3B, C). Synapses were also evaluated by imaging and an analysis of mean Brp intensity across all of the synaptic regions of the *Drosophila* brain (Fig S3A). In almost all regions, knockdown of *crq* in glia produced a significant increase in signal intensity. Thus, Crq acts to regulate synaptic protein levels broadly across the brain. To evaluate whether this was due to a change in the number of presynaptic structures, we counted the number of Brp^+ puncta in the antennal lobes (Fig 3D, E). We observed an increase in puncta number in this region, suggesting that an increased number of synapses is at least partially responsible for the increase in synaptic protein levels we observed. Besides presynaptic Brp, *crq* knockdown in glia also resulted in increases in levels of an additional presynaptic protein, Syt7[53] (Fig 3F) and a postsynaptic protein, Dlg1[54] (Fig 3G). These results indicate that Crq in glia coordinately regulates multiple synaptic proteins, and therefore likely synapses themselves.

A unique advantage of using *Drosophila* to study synapse formation and elimination is that we can monitor these processes in desired subsets of neurons. Using existing models, the field has been limited in the subtypes of neurons which can be studied based on the small number of neuronal subtypes that

can be successfully cultured *in vitro* without glia, and *in vivo* to subsets of excitatory neurons in primary sensory areas that can be clearly labeled and manipulated. In contrast, there are thousands of driver lines that allow cell-type specific visualization and manipulation of different neuronal subsets in the fly[55], and these can be used to express synaptic labels specifically in those cells[56]. To evaluate the effect of manipulating Crq expression on synapses in specific populations of neurons, we expressed a synaptic label in two populations: Or82-expressing neurons that are part of the olfactory system[57], and ppk neurons, which regulate thirst behavior in the adult brain[58]. In Or82a neurons, knockdown of c*rq* in glia resulted in an increase in presynaptic puncta at 3 dpe, consistent with what we observed when assaying synapses globally (Fig 3H, I). Interestingly, these differences were not present at 0 dpe (Fig 3H,I). This supports the notion that these Crq-dependent changes were acquired during the dynamic period of synaptic remodeling that we found occurs during early adulthood, rather than the time of initial circuit formation. Similar to what we observed in Or82a$^+$ neurons, *crq* mutants did not exhibit differences in synapse number compared to controls in ppk$^+$ neurons at eclosion, but a substantial increase presynaptic puncta in *crq* mutant flies was evident by 3 dpe (Fig 3J, K).

Crq mutants and *crq* knockdown in all glia resulted in an increase in synapses. To determine the glial subtype responsible for these changes, we first assessed in which cell types *crq* is expressed using a *crq* transcriptional reporter to drive a nuclear label (Fig S3B). When co-staining with a marker for all glial nuclei (repo), we found that >90% of cells expressing *crq* were glia and this was consistent across all ages (Fig S3C). In line with this, knockdown of *crq* in all glia significantly increased Brp-GFP levels, while knockdown in neurons had no effect (Fig 3L). The *crq* transcriptional reporter also showed a decrease in the levels of *crq* expression over developmental time (Fig S3D). Interestingly, this drop in *crq* expression coincides with the decrease in developmental synapse elimination we had observed previously (Fig 1J).

Next, we knocked down *crq* in different subtypes of *Drosophila* glia: astrocytes, the glial subtype in direct contact with most synapses in the *Drosophila* brain; cortex glia, which are associated with neuronal cell bodies; and ensheathing glia which sit in between those two regions[59]. As expected, knockdown of *crq* just in astrocytes produced a significant increase in Brp-GFP levels, while crq knockdown in ensheathing glia did not (Fig 3L). Surprisingly, knocking down *crq* in cortex glia also resulted in an increase in Brp-GFP levels (Fig 3L), even though these cells have no direct contact with synapses. One possible explanation could be that, in addition to selective elimination of synapses, whole neuron elimination could contribute to the decrease in synapses observed during development, and perhaps knockdown of *crq* in cortex glia might prevent the elimination of neuron cell bodies. However, when we labeled neuronal nuclei (elaV) and co-stained with an antibody that recognizes cleaved Dcp1 to label dying cells, we found no instances of cleaved Dcp1$^+$elaV$^+$ cells (Fig S3E). There were only up to 3 total cleaved Dcp1$^+$ cells per brain during the time points when synapse elimination occurs, and no difference in these numbers was observed when *crq* was knocked down in glia (Fig S3F). While the role of cortex glia in this process remains to be illuminated, our data suggest that astrocytes may act in cooperation with other glial cell types to effectively eliminate synapses from the brain, and that this cooperative process requires Crq.

Crq regulates synaptic engulfment

The increase in synapses observed with loss of Crq could be due to increased synapse formation or decreased synapse elimination. Based on Crq's known role in debris clearance in the immune system[60], we anticipated that Crq would be involved in synapse elimination. To assess this, we first evaluated

whether knockdown of *crq* affected levels of the genetically encoded engulfment markers, FYVE-GFP (Fig 4A, B) and spn-RFP (Fig 4A, C) that are expressed in astrocytes at high levels at 3 dpe. Indeed, we found that knockdown of *crq* in astrocytes strongly reduced these markers of engulfment. To ensure that *crq* knockdown did not simply interfere with the genetic expression of these constructs, we also used a non-genetically encoded marker of engulfment activity, LysoSensor, which labels acidic lysosomes in live brain tissue (Fig S4A). Similar to the other engulfment markers, *crq* knockdown resulted in a significant reduction in LysoSensor signal across the brain compared to controls (Fig 4D). We did not observe any gross changes in astrocyte distribution or morphology (Fig S4C), and therefore the changes we see in astrocyte engulfment markers are not likely due to diminished astrocyte number or infiltration. Together, these results argue that Crq is required for the phagocytic activity of glia during early adulthood.

Using a *crq* transcriptional reporter, we had seen that *crq* expression begins to decrease after 3 dpe (Fig S3D). We wondered whether this reduction in *crq* expression might actually cause the decrease in glial engulfment observed between 3 dpe and 10-12 dpe. To test this, we generated a fly in which *crq* is expressed under UAS control so that we could overexpress *crq* using an astrocytic Gal4 driver, not subject to its normal patterns of transcriptional regulation across development. We found that *crq* overexpression in astrocytes resulted in an increase in both FYVE-GFP (Fig 4E, F) and spn-RFP (Fig 4E, G) engulfment indicators at 3 dpe. Furthermore, this increase was maintained out to 10-12 dpe, suggesting that *crq* expression is sufficient to drive continued glial phagocytic activity, even past the developmental time to which this process is normally restricted.

To further explore whether Crq regulated glial engulfment of synapses, we used the Brp-eGFP-mCherry flies we generated and evaluated the number of $eGFP^{-}mCherry^{+}$ puncta, indicative of synapses which have undergone engulfment (Fig 4H, I). Indeed, we found the knockdown of *crq* in glia resulted in significant reductions in $mCherry^{+}$ signal, arguing that Crq is required for normal levels of developmental synaptic engulfment.

Crq is required for developmental and age-related synapse elimination and proper circuit function

If Crq regulates synaptic engulfment, we would expect synapse elimination to be attenuated in flies in which *crq* is knocked down in glia. When we established the time course of synapse development in the fly, we had identified that synaptic protein levels decrease between 3 and 10-12 dpe (Fig 1C). When we knocked down *crq* in glia, this reduction in synapses during development no longer occurred (Fig 5A), indicating that Crq is required for developmental synapse elimination.

We had also observed a decrease in Brp-GFP signal evident between 10-12 and 30-35 dpe, which suggests *Drosophila* experience a period of age-related synaptic loss (Fig 1C). Since knockdown of *crq* prevented the decrease in synapses we observed during development, we asked whether it might also attenuate this synaptic decrease associated with age. Remarkably, *crq* knockdown in glia also completely prevented this age-related decrease in Brp-GFP protein levels (Fig 5B). This argues strongly that synaptic loss is not a passive and inevitable process, but that it is actively regulated. Furthermore, modifying glial function is sufficient to block age-related decreases in synaptic proteins. Interestingly, the previously defined glial engulfment receptor $Drpr^{61}$ was not required for age-related synaptic loss to occur (Fig S5A), suggesting that Crq is unique compared to other known astrocytic phagocytic receptors in its ability to regulate age-related reductions in synaptic protein levels.

It is possible that Crq could be required for glia to engage in engulfment regardless of substrate or context, or rather it may specifically mediate selective synapse elimination. To test this, we assessed whether glia in which *crq* was knocked down could successfully engage in elimination of synaptic debris during metamorphosis and clearance of neuronal debris after injury. During metamorphosis, glia clear virtually all synapses from the larval nervous system in preparation to construct the nervous system of the adult fly[62] (Fig S5B). We did not find any changes in clearance of synaptic debris in this context with glial *crq* knockdown (Fig S5C). To test whether Crq was required for clearance of neuronal debris after injury[61], we unilaterally ablated a maxillary palp, injuring sensory neurons that project into the antennal lobes within the brain, and simultaneously labeled a subset of those neurons to visualize their projections (Fig S5D). We found that there was no difference in the extent of clearance of these projections when *crq* was knocked down in glia (Fig S5E). Together, these results demonstrate that Crq is not required for glia to engage in engulfment in all contexts, but rather is specifically required for the selective elimination of synapses that occurs in circuit remodeling during synapse development and in aging.

We reasoned that retention of supernumerary functional synapses within fly circuits should affect circuit function. Given that human mutations in *crq*'s ortholog, *SCARB2*, are the cause of a progressive form of epilepsy[47], we evaluated whether *crq* mutants might also exhibit enhanced circuit activity. To test this, we used an assay to assess seizure susceptibility (Fig 5C). The strong sensory stimulus of vortexing flies can result in seizures in flies with heightened circuit excitability, resulting in transient immobility and impaired climbing behavior[63]. In *crq* mutant flies, there was no difference in recovery at 0 dpe, but by 10-12 dpe there was a significant increase in the proportion of mutant flies that failed to recover within 1 minute relative to controls (Fig 5D). Knocking down *crq* in glia produced similar results, with no difference in seizure susceptibility at 0 dpe, a significant increase by 3 dpe, and a further enhancement of this behavior by 10-12 dpe (Fig 5E). The time course of these behavioral changes aligns well with when increased synaptic protein levels were observed in these flies, and with the progressive epilepsy phenotype observed in humans with *SCARB2* mutations. Baseline climbing behavior was impaired in *crq* mutant flies by 10-12 dpe (Fig S5F), but not when *crq* was knocked down in glia (Fig S5G), suggesting that general locomotor deficits are unlikely to account for the measures used to evaluate seizure recovery. Together, these data support the notion that the synaptic increases evident with loss of *crq* result in changes in brain circuitry and behavior. Like changes in synapses, these phenotypes were not present at eclosion, indicating that these effects are driven by changes in synaptic circuitry that occur in the adult fly.

Finally, increased circuit excitability has been shown to impair survival in flies, so we sought to evaluate whether loss of *crq* would impact the fly lifespan[64]. *Crq* mutant flies have been shown to exhibit early lethality due to impaired immune function[65], which we recapitulated here (Fig S5H). However, we also found that knockdown of *crq* in glia also produced survival deficits, albeit much milder than those in *crq* mutants (Fig S5I). If these survival deficits were linked with the increased circuit excitability we observed, we reasoned that we should be able to aggravate this survival deficit in flies which already exhibit increased neuronal activity, such as in Sh^5 (*shaker*) mutants[66]. Indeed, we see that, while Sh^5 flies exhibit no survival deficit on their own, this mutant significantly worsens survival defects in flies in which *crq* is knocked down in glia. Together, these data suggest that the synaptic changes observed in flies lacking *crq* result in progressive circuit dysfunction over the lifetime of the organism.

Discussion:

Synapse formation and elimination contribute to neural circuit development, and require coordination between neurons and glia. Work over the last two decades has identified a number of glial molecules that regulate synapse formation or elimination, but an emerging theme appears to be that glial regulation of synapse numbers is dynamic and mechanistically diverse across the brain. A major aim of this study was to establish *Drosophila* as a system to study conserved genes and pathways that govern broad changes in synapse formation and elimination across the brain, to complement existing *in vitro* and mouse models. We found that *Drosophila* exhibit similar synaptic dynamics over their lifespan as mammals, with periods of developmental synapse formation and elimination, as well as age-related synaptic loss. To explore the molecular basis of glial regulation of synapse numbers, we combined a rapid, ELISA-based screening method with glial-specific gene knockdown by RNAi to identify 48 genes that are conserved in glial expression from flies to mammals, and are required *in vivo* for normal synapse numbers. Finally, we identify the scavenger receptor Crq is required for both developmental synapse elimination and age-related synapse loss, implying that synapse loss with age is actively driven by glial cells.

While our observations ultimately require further confirmation by examining synaptic contacts by other means, and in uniquely identifiable cells over time, our results support the notion that at late pupal development and into early adulthood, synapses are dynamically changing across the *Drosophila* brain. Total synapse number peaks by 3 days after eclosion, and then is reduced over the next week. Given that loss of Crq in glia blocks this decrease in synapse numbers early in adulthood, it appears that glial cells are responsible for promoting early loss of synapses in the adult brain. Consistent with our observations, dynamic changes in synapses have been observed during this time window in response to changes in sensory input[67-69], and these have been shown to be regulated by the glial phagocytic receptor Draper[70].

One reason to establish *Drosophila* as a model to study glial regulation of synapse development was to be able to perform large-scale genetic screens *in vivo* to reveal the diversity of pathways required. Our ELISA-based screen identified a list of 48 genes that, when knocked down in glia, changed synaptic protein levels, reflecting the diversity of ways in which glia can regulate synapse development. Many of the genetic pathways enriched in the screen had not been previously implicated in glial regulation of synapse development. Metabolic and catabolic pathways, transporters, neurotransmitter receptors and sphingolipid regulators all represent new categories of mechanisms that influence synaptic regulation by glia. Others, such as immune-related pathways, have been previously identified as important regulators of synapse development in mammals[71], and our screen results confirm that they represent a major category of genes involved in this process. However, it also highlights that we have not yet identified all types of immune molecules that glia use to regulate synapse development. For example, pattern recognition receptors and scavenger receptors were novel classes of molecules identified as synaptic regulators in this screen. Multiple members of the Toll receptor family were identified, as well as secreted antimicrobial peptides and molecules involved in innate immune memory. Therefore, even in the relatively well studied area of immune-related molecules, our data suggest we still have much more to discover about the diversity of ways immune molecules can be repurposed in the context of glial regulation of synapse development.

The overarching goal of this screen was to identify starting points to build our understanding of the rules that neurons and glia use to decide when and which synapses should be formed and eliminated across the lifespan. Our discovery of Crq as a glial regulator of synapse elimination reveals new insights into this

process. First, we found that the timing of *crq* expression tightly correlated with that of synapse elimination. Therefore, the downregulation of *crq* expression may be a way in which glia limit when during development synapse elimination is allowed to occur at high levels. Indeed, extending expression of *crq* later in development was sufficient to promote continued expression of phagocytic markers in glia. Understanding how Crq is regulated and signals may provide further insight into how glia decide when to promote synapse elimination and tune the relative balance of synapse formation and elimination across development. Because Crq seems to act as such a potent and sustained regulator of synapse elimination, identifying its ligand would also open up the opportunity to understand how the right synapses are selected for elimination.

Crq has also provided a handle to start understanding how different glial subtypes may work together to regulate synapse development. While astrocytes are the only glial cell type within the synaptic neuropil in *Drosophila*, *crq* knockdown just in astrocytes or just in cortex glia was sufficient to alter synaptic protein levels, suggesting that cortex glia may coordinate with astrocytes to facilitate synapse elimination in some way. There is precedence for the phenomenon of coordination among glial cell types in regulating synapse development in mammals[72], and future work in *Drosophila* could allow us to dissect the transcellular signaling pathway involved.

Our characterization of Crq further reveals that glia employ different receptors to mediate clearance of synapses and other neuronal debris in a context-dependent manner. While knockdown of both *crq* and *Drpr* (othologous to *MEGF10*) increased levels of synaptic proteins at 3 dpe, only Crq was required for glial-mediated synaptic loss in aging, and only Drpr was required for glial engulfment of debris during metamorphosis[62] and after injury[61]. Why would glia use distinct pathways to mediate engulfment in these different contexts? It is known that Drpr activation promotes initiation of large-scale transcriptional changes that amplify their engulfment activity[73]. Perhaps this is beneficial in situations like metamorphosis, when virtually every synapse, along with axonal and dendritic debris, needs to be rapidly cleared from the nervous system. However, this amplification of engulfment activity may be unnecessary or undesirable when fine-tuning synaptic connectivity, thus requiring a different downstream signaling mechanism. In addition to Drpr and Crq, knockdown of other immune receptors, including other members of the scavenger receptor family, also altered Brp-GFP levels in our screen. This indicates that different receptors, even from the same class, are unable to compensate for loss of the others. It is possible that they recognize different ligands, act on different subsets of synapses, or act in a convergent pathway that requires all of them to be present. Having multiple developmental checkpoints in place may give glia more power to precisely tune their engulfment, ensuring restriction of synapse elimination to appropriate times and places.

Our work supports the emerging connection between mechanisms used to mediate synaptic elimination in development and pathological synaptic loss. Here, we found that glial Crq was required for synaptic loss in aging. In mammals, there is also precedence for reuse of complement proteins in synapse elimination in development and disease[15,74-76]. This begs the question of whether Crq might also mediate synapse elimination in other contexts of pathology, in response to injury, neurodegeneration or immune activation. The orthologs of *crq*, *SCARB2* and *CD36*, have been implicated in a number of neurological diseases, suggesting that this may indeed be the case. *SCARB2* mutations are the genetic cause of a rare, progressive form of epilepsy[47], though how these mutations cause disease is unknown. Crq mutants and *crq* knockdown in glia both confer progressive increases in seizure susceptibility over the course of development, similar to the pattern of clinical progression observed in *SCARB2* mutant carriers. Perhaps

the excess retention of synapses due to impaired synaptic engulfment by glia underlies this clinical phenotype. In addition, variants in *SCARB2* and *CD36* are associated with autism[48], Alzheimer's disease[49,50] and Parkinson's disease[51,52]. Possibly the same mechanisms that these receptors use to regulate appropriate elimination of synapses in development may also contribute to synaptic pathologies that underlie these diseases. Multiple CD36 inhibitors have been approved for therapeutic use in humans, and mouse models of these associated diseases may be the best place to evaluate whether pharmacological inhibition of these receptors could be beneficial in limiting pathological synaptic loss.

Together, our efforts using a high-throughput ELISA-based *in vivo* forward genetic screening approach in *Drosophila* has increased our knowledge of the breadth of genes glia employ to regulate synapse development, and allowed us to study Crq as a starting point to begin decoding how glia decide when and which synapses to remove. In combination with existing *in vitro* and mouse models, we now have a powerful arsenal of complementary systems to answer the fundamental question of how glia act to establish appropriate circuits in development, and address the pressing need to understand how these processes contribute to pathological synaptic changes that lead to circuit dysfunction in disease.

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Author contributions:

Conceptualization, TRJ, YK and MRF; Methodology, TRJ; Investigation, TRJ, VOM, MKBM, VKP, YK, JC and AS; Writing – Original Draft, TRJ; Writing – Review & Editing, TRJ, YK and MRF; Supervision, TRJ and MRF; Funding Acquisition, TRJ, YK and MRF. All authors read and approved this manuscript.

Declaration of Interests:

The authors declare no competing interests.

Figure titles and legends:

Figure 1: *Drosophila* use conserved glial mechanisms to regulate synapse development and maintenance across the lifespan

(A) Formation of the adult fly circuitry begins at late pupal stages (48-96 hr after puparium formation) and in this study we evaluated glial and synaptic changes that occurred from this time point through the rest of the fly lifespan (30-35 dpe^{+}). To visualize and evaluate synapses, the synaptic protein Brp was endogenously labeled with GFP (B), and gene expression was manipulated in all glia using *repo-Gal4* or

just in astrocytes using *alrm-Gal4*. (C) Brp-GFP protein levels were analyzed by ELISA in fly heads collected at the indicated time points. (D) Images were acquired from fly brains in which astrocytes express FYVE-GFP, a PI3P marker, which labels endosomes and early phagosomes. (E) Images were thresholded and the percent $FYVE^+$ area evaluated. (F) The late phagosomal marker spn-RFP was expressed in astrocytes and (G) the percent spn^+ area measured. (H) We developed a tool to evaluate synaptic engulfment in which a pH-insensitive mCherry and a pH-sensitive eGFP were knocked into the endogenous Brp locus. (I) eGFP and mCherry signal were visualized and (J) the number of $mCherry^+eGFP^-$ puncta quantified across the brain. (K) We performed TRAP sequencing to evaluate genes translated in astrocytes across late pupal stages (48-72hr APF) through the adult lifespan. Differences in expression across the 100 most differentially expressed genes (red - high, blue - low) was plotted. (L) FPKM values were extracted from the TRAPseq dataset for *tsp*, *sparc* and *drpr*. (M) RNAi's were used to knockdown each of these genes in glia and Brp-GFP levels were measured by ELISA. Results for each gene was normalized to the control average and one sample t-tests performed relative to 1.

Figure 2: An *in vivo* genetic screen identifies glial regulators of synapse development

(A) A screen to identify glial regulators of synapse development was performed in male *Drosophila* at 3 days post eclosion (dpe). Flies expressing Brp-GFP and the glial driver *repo-Gal4* were crossed with 971 selected *UAS-RNAi* lines. Three samples with three heads each were collected from each cross. Heads were homogenized and GFP protein concentration measured from these lysates using an ELISA assay. (B) For each gene, we calculated the fold change and p-value relative to controls (Brp-GFP, *repo-Gal4* flies crossed with an isogenic control line). On the left, in red, are genes that, when knocked down in glia, reduce Brp-GFP levels and those to the right, in green, are genes that when knocked down, increase Brp-GFP. (C) Hit criteria were defined as genes that when knocked down resulted in a >25% fold-change in Brp-GFP levels with a $p<0.01$, and genes with a >15% change and $p<0.05$ were also identified. (D) Gene ontology analysis on all identified genes was performed and the top 10 significantly enriched biological pathways associated with genes whose knockdown increased Brp-GFP was determined. (E) Network analysis was performed on the top 30 differentially expressed pathways with edges representing the number of shared genes between these pathways. (F,G) These analyses were repeated on genes that when knocked down in glia decreased Brp-GFP levels. In (E) and (G) lowercase roman numerals correspond to the dendrograms of pathway relationships in Fig S2.

Figure 3: Loss of glial Crq increases synapse numbers in development

(A) Brp-GFP levels were measured by ELISA when each of the available RNAi lines was used to knockdown *crq* in glia and results compared to isogenic controls (dotted line). (B) Brp-GFP protein levels were evaluated by Western blot in two crq mutant lines, $crq^{MI12323}$ and $crq^{CR02509}$ and *yw* controls. (C) Brp levels were normalized to β-tubulin. (D) Endogenous Brp-GFP signal was imaged in the antennal lobe and (E) the density of Brp^+ puncta number evaluated. (F) GFP protein levels were assessed by ELISA from flies expressing endogenously tagged Syt7-GFP and (G) Dlg1-GFP. (H) Synapses were labeled with Brp-short-mCherry in Or82a neurons, a subset of neurons which project to a single glomerulus within the fly antennal lobe. (I) The number of synapses across the volume of the glomerulus were quantified. (J) Synapses within ppk-expressing neurons were visualized using Brp-short-GFP in control (*yw*) and $crq^{MI12323}$ mutants and (K) the number of GFP^+ puncta per hemibrain quantified. (L) Crq was knocked down in all glia (*repo-Gal4*), neurons (*elaV-Gal4*), astrocytes (*alrm-Gal4*), ensheathing glia (*GMR56F03-Gal4*) and cortex glia (*cortex glia split-Gal4*) and Brp-GFP levels measured and normalized to a control in

which the indicated Gal4 was expressed alone (dotted line). All experiments in this figure were performed at 3 dpe except where otherwise indicated. Male and female files were pooled across these experiments.

Figure 4: Crq regulates glial synaptic engulfment

(A) FYVE-GFP and spn-RFP engulfment indicators were expressed astrocytes and (B) the percent $FYVE^+$ area and (C) spn^+ area quantified. (D) Lysosensor was applied to acutely dissected fly brains and the signal quantified within the neuropil. (E) FYVE-GFP and spn-RFP were expressed in astrocytes and the signal assessed in controls compared to flies in which an astrocyte driver is used to express *UAS-crq*. (F) The percent $FYVE^+$ and (G) spn^+ area were quantified and normalized to 3 dpe controls. (H) Brp was endogenously labeled with a pH-sensitive eGFP and a pH-insensitive mCherry. The signal was overlayed and (I) the number of $eGFP^-mCherry^+$ puncta (shown magnified in insets) quantified. All experiments were performed at 3 dpe using males and females unless otherwise specified.

Figure 5: Crq is required for developmental and age-related synapse elimination and proper circuit function

(A) Brp-GFP levels were quantified in fly head lysates by ELISA across development and (B) aging. (C) A seizure-susceptibility assay was used in which flies are vortexed and recovery scored by evaluating the number of flies that resumed normal climbing behavior after 1 min. (D) Recovery from vortexing was scored in *yw* controls and $crq^{MI12323}$ mutants. Chi-squared tests were used to evaluate differences between these two genotypes at the developmental stages indicated. (E) Recovery from vortexing was scored in control *repo-Gal4* flies crossed with VDRC isogenic controls and with knockdown of *crq*.

Tables with titles and legends:

N/A (no main text tables)

STAR Methods:

Fly stocks and maintenance:

Drosophila were housed at 25°C in a 12 hr light-dark cycle. Except where noted below, flies were maintained on cornmeal-molasses media. For circadian experiments, no additional protocols were in place to ensure strict circadian entrainment. Larvae were collected at wandering stage 3 (wL3), pupae for experiments evaluating synaptic elimination in metamorphosis were collected at head eversion, a developmental event that occurs ~12 hr into metamorphosis. "Late pupae" were collected at 72-96hr APF. Adults were collected at time points across the lifespan: flies denoted as "0 dpe" were collected within 24 hr of eclosion, "3 dpe" were collected within 48-72 hr of eclosion, and those the other age ranges are as stated. Existing fly lines used in this study included: *pUAST-mCD8::GFP*[77], *repo-Gal4*[78], *alrm-Gal4*[79], *GMR25H07-Gal4*[55], *per[01]*[80], *UAS-pWiz-drpr RNAi7b*[61], *Brp-GFP* ($brp^{MI02987\text{-}GFSTF}$)[81] (BL#59292), *UAS-GFP-2xFYVE* (BL#42712), *UAS-Spinster(Spn)-mRFP* (BL#42716), *UAS-tsp RNAi* (BL#34661), *UAS-sparc RNAi* (BL#40885, HMS02133), *UAS-crq RNAi#1* (VDRC#45884), *UAS-crq RNAi #2* (VDRC#45883), *UAS-crq RNAi#3* (BL#40831), *UAS-crq RNAi #4* (BL#42811), *crq[MI12323]*[81] (BL#57926), *crq[CR02509]*[82] (BL#93353), *Syt7-GFP* (BL#94776), *dlg1-GFP*[81] (BL#59417), *Or82a-lexA, lexAop-brp.short.mCherry* (gift from Mary Logan), *UAS-brp-short-GFP*[56] , *GMR56F03-Gal4*[83] (BL#39157), *Ctxglia-*

split-Gal4 (*wrapper-Gal4DBD, Nrv2-VP16AD*)[84], *Sh[5]* (BL#111), *Or85e-mCD8::GFP*[85], *crq-Gal4* (BL#25041), *UAS-H2B:mCherry.HA* (gift from Josh Dubnau).

In this study, we generated two new fly lines: *UAS-crq* and *Brp-eGFP-mCherry*. For the *Brp-eGFP-mCherry* fly, *mCherry* was amplified from Addgene plasmid #32002 and the *eGFP* (actually *eGFP-FlAsH-StrepII-TEV-3xFlag*) amplified from DGRC plasmid #1298. These were assembled using HiFi assembly and put into the DGRC #1297 backbone. The sequence was verified using Plasmidsaurus and injected BDSC stock BL#37403 using the MiMIC injection service from BestGene. The *UAS-crq* was made by amplifying 1.4kb of *crq* from cDNA RE02070 and Gibson assembly used to insert this DNA into the NotI site of the *pattB-5xUAS* plasmid. This was injected by BestGene into stock BL#24749 to insert it at the ZH-86Fb attP site.

TRAP Seq:

This dataset is publically available through GEO (accession #GSE242729) and the methods for obtaining these results have been detailed previously[27]. Briefly, an eGFP-tagged L10a ribosomal subunit was expressed in astrocytes using *alrm-Gal4*, *elaV-Gal80*. Pupae were collected at 48-72hr after puparium formation (APF), and adults collected at 1-3 dpe, 10-12dpe and 50-60dpe. Two hundred flies were pooled for each sample, and 3-5 samples were evaluated at each time point. Ribsomes were precipitated with beads, and associated RNA isolated. cDNAs were prepared and the sequencing library prepared using ribosomal reduction. Sequencing was performed on a NovaSeq flow cell with 50 million templates per sample. Fastq files were assembled using bcl2fastq. Differential gene expression was evaluated using DEseq2. Heatmaps were assembled using the heatmaply package in R.

ELISA:

ELISAs were performed to detect GFP concentrations from flies expressing *Brp-GFP*, *Syt7-GFP*, *dlg1-GFP* and *GMR25H07-Gal4, UAS-mCD8::GFP* in which astrocyte membranes were labeled with GFP. 96-well plates (Immunolon 2HB, Thermo #3455) were coated with 100µl 1:5000 dilution of chicken anti-GFP antibody (Abcam #ab13970) in carbonate buffer (30mM sodium carbonate, 70 mM sodium bicarbonate, pH 9.6), sealed and left to shake overnight at 4°C. Plates were washed 4 times with 0.1% PBST and 350µl of blocking buffer (2% milk in 0.1% PBST) added, plates sealed and left to shake overnight at 4°C. Samples were prepared from flies which had been frozen and kept at -80°C until use. Heads were removed by vortexing frozen flies and heads were placed into a 1.5mL Eppendorf tube. Samples were homogenized using a hand-held homogenizer in 120µl 0.1% PBST for 5 s and placed on ice. After all samples were prepared, samples were centrifuged at 13,000 rpm for 2 min at 4°C. Plates were washed 4 times with 0.1% PBST and 100µl of the head homogenate supernatant for each sample was loaded into the plate. The plate was sealed and samples were incubated at 37°C for 90 min. Samples were then removed, the plate washed 4 times with 0.1% PBST. 100µl of a 1:2500 concentration of mouse anti-GFP antibody (Cell Signaling Life Technologies #A-11120) prepared in blocking buffer was added. The plate was sealed and left to shake overnight at 4°C. The plate was washed 4 times with 0.1% PBST and then 100µl of a 1:2000 concentration of donkey anti-mouse HRP (Jackson ImmunoResearch #715-035-150) in blocking buffer was added, the plate sealed and left to shake overnight at 4°C. The plate was washed 4 times with 0.1% PBST. 100µl of a 1:1 solution of TMB substrate and peroxide solutions (TMB substrate kit, Thermo #34021) added to each well. The plate was allowed to develop for 30 s – 2 min, depending on the time required for all samples to develop within the linear dynamic range of the assay. At this time, 100µl of 1N HCl was added to all wells. Optical density values at 450 and 630 nm were read on a colorimetric plate reader. OD values for each well were determined by subtracting the values from the

630nm wavelength from the 450nm reading. The average OD values for blank wells on the plate, in which PBST had been added in place of samples, was then subtracted from these values for each sample. These are the values reported as OD values throughout the paper. In some experiments, these were normalized to the average OD values of control samples, allowing comparison of results across plates. For additional details and about this protocol, see our previous methods paper that details this protocol and additional possible variations[24].

Screen:

For the screen, we compiled a list of genes from existing literature and identified *Drosophila* orthologs using DiOPT. Lines to target these genes were identified from VDRC[44] and up to two lines selected with < 2 predicted off-targets. These lines were crossed with flies expressing *Brp-GFP, repo-Gal4*. ≥ 9 male progeny of the desired genotype were collected at 3 dpe (48 to 72 hr after eclosion). 45 lines were deemed to be lethal, as they produced 1 or fewer progeny of the appropriate genotype and >100 flies eclosed. There were, in addition, several lines that we were unable to collect the total required 9 flies from, either because the proportion of the correct genotype produced was very low, or only females of the appropriate genotype were produced. These were not considered lethal and were excluded from our analyses.

Flies were frozen over time as they were collected (typically between ZT23 and ZT1) and stored at -80 until use. For each screening sample, three fly heads were homogenized and then the lysates diluted 2x, such that the equivalent concentration of 1.5 fly heads was loaded. This was initially done to allow us to perform 2 technical replicates for each sample, but an interim analysis revealed that this conferred very little advantage in reducing sample variability, and therefore we used only one technical replicate per sample for the remaining screen. Three samples were prepared from flies from each genotype, representing 3 biological replicates. ELISAs and analysis were performed as described above, normalizing each sample to the average of the control samples (*Brp-GFP, repo-Gal4* crossed with a VDRC isogenic control line – VDRC#60000) run on each plate. The fold change and p-value were determined using 1-way t-tests relative to 1. No corrections were made in p-values to correct for multiple comparisons, which with a cut-off of $p<0.01$ for ~1000 lines could generate ~10 false positive results. However, because we were quite limited in statistical power with an n of 3 per sample, we chose to be relatively liberal in these cut-off values, and opt to replicate potential hits in follow-up secondary screens. We categorized "hits" as those genes that when knocked down resulted in a >25% change from controls with a $p<0.01$ and "possible hits" that warrant further analysis as those with >15% change with $p<0.05$. Genes identified in the screen as "hits" or "possible hits" were subjected to gene ontology analysis using ShinyGo[86]. The top 30 differentially expressed pathways were analyzed and networks prepared from those categories that contained >3 genes in common.

Imaging:

For imaging, adult fly heads were removed from fly bodies and placed in a 4% PFA solution prepared in PBS for 20 min at room temperature. Heads were then briefly washed and dissected in PBS with 0.1% TritonX (0.1% PBST). Brains were kept in this solution on ice for up to 20 min. They were then transferred to 4% PFA prepared in PBS and fixed at room temperature for 20 min, and briefly washed in 0.1% PBST. For brains in which only endogenous fluorescent signal was to be evaluated, brains were then either transferred to Vectashield mounting media and mounted onto slides directly, or stored in 0.1% PBST at 4°C for up to 3 days, and then mounted. For brains that were subjected to staining, brains

were instead transferred to 0.5 mL Eppendorf tubes and incubated in 0.5% PBST for 1 hour. Brains were then transferred into primary antibody solution (GAT 1:3000, developed by T. Stork), repo (8D12, developed by C. Goodman, 1:10), elaV (DSHB 7E8A10, 1:10), cleaved Dcp1 (Cell Signaling #9578, 1:1000), GFP (Life Technologies #A11120, 1:200) in 0.5% PBST at 4°C over 3 nights. Brains were then washed 3 times for 20^{+} min in 0.5% PBST and transferred to a secondary antibody solution (Alexa Fluors at 1:250 dilution) and incubated at 4°C over three nights. Brains were then washed 3 times, transferred to Vectashield mounting media and mounted onto slides.

Third instar larval and pupal brains collected at head eversion, ~12 hr after puparium formation. Brains were dissected in PBS and transferred to 4% PFA on ice until all samples were collected. They were then transferred to RT and fixed for 20 additional min. Brains were then washed, transferred to Vectashield and mounted.

Lysosensor:

For LysoSensor experiments, heads were not prefixed, but brains dissected directly in live imaging buffer (Schneider's Drosophila media + 1% pen/strep, 1% FBS and 10 µg/mL human insulin). A 1µM concentration of LysoSensor Blue (DND-167 #L7533) was added to the brains for 5min. Brains were then briefly washed two times with fresh live imaging buffer and mounted directly onto slides in this buffer. Imaging was performed within 30 min of dissection.

Imaging and analyses:

All images were acquired on a Zeiss 880 confocal microscope, using traditional confocal imaging or Airyccan Fast imaging, as noted for each experiment below. For those image acquired with Airyscan, Airyscan processing was performed using automated settings in Zen Software. Image analyses were performed using Image J, except where noted below. Experimenters were blinded to genotype and time point when performing these analyses.

Mean intensity of Brp-GFP signal was evaluated across all the neuropil regions of the adult *Drosophila* brain that were accessible to imaging. Endogenous Brp-GFP signal was acquired using traditional confocal microscopy, with z sections taken every 5 µm through the anterior half of the brain, ~10-12 slices. Below this depth, there was increasing difficulty in capturing Brp-GFP signal and thus we were unable to evaluate Brp-GFP levels in the most posterior neuropils. Because the neuropil structures are bilaterally symmetrical, Brp-GFP signal was quantified in one hemibrain for each fly. In each z plane acquired, each region of the neuropil was separately outlined and the mean intensity of Brp-GFP signal measured. All neuropils present in each z plane were quantified. Then the mean intensity values for each z slice were averaged to generate one mean intensity value for that region for each fly and region.

The percent area of FYVE-GFP and spn-RFP was quantified over time and when crq was knocked down from images acquired using traditional confocal microscopy. 5-7 z planes spaced 5 µm apart were acquired and max z projections performed. The brain was then outlined as the ROI and the signal within manually thresholded. The percent positive area within this ROI was then measured. For analyses of FYVE-GFP and spn-RFP area in flies expressing UAS-crq, images were acquired using Airyscan Fast imaging. 5-7 z planes were acquired 5 µm apart. For analysis, 3 representative z slices were selected across these z slices. ROIs were drawn around brain and images manually thresholded. The percent positive area was quantified for each of these z slices individually and then averaged to generate the

percent positive area measurement for each fly. These results were then normalized to the average value for 3 dpe controls for each genotype.

Engulfed synaptic material was analyzed by counting the number of mCherry^{+}eGFP^{-} puncta present in brains from Brp-eGFP-mCherry flies. Images of the central brain were acquired using Airyscan Fast, with 7-9 z slices acquired 5 µm apart. eGFP and mCherry signals were overlayed and the mCherry^{+}eGFP^{-} marked. These marks were cross-referenced against the mCherry and eGFP only channels to ensure that these puncta were only mCherry^{+}. The number of mCherry^{+}eGFP^{-} puncta across all acquired slices were quantified and then divided by the total area analyzed.

The number of Brp-GFP^{+} puncta were analyzed across three different experiments. In all experiments, images were acquired using Airyscan Fast imaging encompassing the region of interest with z sections taken 0.2 µm apart through this region. In flies expressing Brp-GFP endogenously across the brain, Brp-GFP puncta number was quantified in the antennal lobe. For each slice, this ROI was outlined and the area outside of the ROI cleared. We initially did this through the entire glomerulus, but pilot experiments demonstrated that analysis through a volume of 7-10 z slices gave very similar results to analysis through the entire volume, so only this 7-10 slice subset was used for analysis. The area of the ROI in each z section was measured and multiplied by 0.2 to obtain the volume of the area analyzed. To analyze puncta number, we scrolled to the middle of the z stack and adjusted the brightness and contrast to use the whole distribution of values and then converted the images from 16 to 8 bit. We then used the Auto Local Threshold function using the Bernsen method with a 12 px radius. After images were thresholded, we used the 3D objects counter analysis tool with a size filter of 10 – 2000, and selected to exclude objects on edges. Maps were shown so the experimenter could evaluate the accuracy of counting. The number on puncta was extracted from the results summary. This number was then normalized to the volume of the area analyzed.

For evaluating Brp-short-mCherry^{+} puncta number in the Or82a glomerulus, a very similar analysis protocol was used to that described above, except that it was not necessary to outline the region of interest because the synaptic label was already exclusively expressed in these neurons. We also analyzed synapse numbers across the entire glomerulus volume, to capture the total synapse number across the population, and therefore did not calculate or normalize to the volume of the ROI.

For evaluating Brp-short-GFP^{+} puncta number in ppk neurons, we used Imaris analysis software. The "spot" function was used to automatically annotate GFP^{+} puncta across the volume of the image. This was then proofread by the experimenter and corrections made manually as needed. Imaris then reported the total number of spots across the population for each image. Like with the Or82a neurons, we did not normalize to volume of the ROI in this case, because synaptic labeling was restricted to ppk neurons.

Crq expression was analyzed from images in which *crq-Gal4* was used to drive the nuclear transcriptional reporter *UAS-H2B:mCherry.HA*. These images were acquired using traditional confocal imaging with 7-10 z planes acquired spaced 5 µm apart. Brains were co-stained with the glial nuclear marker repo as described above. mCherry and repo signals were overlayed. The number of all crq^{+}, repo^{+}crq^{-} and crq^{+}repo^{-} nuclei were counted across 3 representative z planes. These numbers were then used to determine the percent of repo^{+} cells that were also *crq*$^{+}$ and also the percent of *crq*$^{+}$ cells that were repo^{+}.

Neuronal death was evaluated by staining sections with elaV, a marker of neuronal nuclei, and cleaved Dcp1 to label dying cells. Images were acquired 2 µm apart through approximately half of the *Drosophila* brain to 50-70 µm in depth. Cleaved Dcp1$^+$ cells were counted across this entire volume. Overlays of these two signals were used to determine whether Dcp1$^+$ cells were neurons.

LysoSensor signal was analyzed in images acquired using Airyscan Fast imaging. This experiment was performed in a background in which flies expressed *GMR25H07-Gal4, UAS-mCD8::GFP* which was used to allow clearer visualization of the neuropil. Three z planes 5 µm apart were imaged. Because this was done on live tissue rather than in mounting media, photobleaching prevented evaluation of this signal across a larger volume. Lysosensor$^+$ area was evaluated within the neuropil of the antennal lobe, since pilot data suggested that this produced similar results to analysis across all the neuropil regions within our imaging window. The ROI outlining the antennal lobe was adjusted as needed to exclude imaging artifacts, in particular autofluorescent signal from the trachea. Thresholding to identify LysoSensor signal was performed manually and the percent area averaged across the 3 brain slices.

Brp-GFP area was performed in larvae and pupae. Images were acquired using Airyscan Fast and underwent Stiching before proceeding to AiryScan Processing using Zen Software. An ROI was drawn around the neuropil of the ventral nerve cord for each z plane and manual thresholding was used to capture the Brp-GFP$^+$ area. This was done across 3 representative z planes and then averaged.

To evaluate clearance of Or85e neuronal debris after injury, an injury was performed in which one maxillary palp was removed from the fly. Seven days later, brains were dissected, fixed and stained for GFP to visualize the Or85e-mCD8::GFP signal. Images were acquired using traditional confocal imaging through the entire depth of the labeled glomeruli with z sections 1 µm apart. The volume of the glomerulus on the injured and uninjured size were determined by manually outlining the GFP$^+$ area that marked each glomerulus through each z plane. These were then added together to determine the total volume for each glomerulus. The percent volume of the injured compared to the uninjured glomerulus was then calculated.

Western blot:

Flies were frozen and stored at -80°C until use. Heads were removed by vortexing and 3 heads per sample prepared in 1.5mL Eppendorf tubes. Samples were homogenized in PBS and Laemmeli buffer containing β-mercaptoethanol added. Samples were boiled for 5 min and spun down briefly. The supernatant was loaded into a 4-20% Tris-Bis Gel and run at 100V for ~1 hr in Tris-glycine running buffer with 8% SDS. The gel was transferred to a PVDF membrane at 33V overnight at 4°C in a Tris-glycine transfer buffer containing 12% methanol. The membrane was blocked in 5% BSA in TBS with shaking for 1 hour at RT. The membrane was cut and incubated with nc82 antibody against Brp (DSHB nc82, 1:50), or β-tubulin antibody (DSHB E7, 1:1000) overnight at 4°C. Membranes were washed 3 times for 20 min in TBS and incubated in HRP conjugated secondary antibody (Jackson ImmunoResearch, 1:5000) in 5% BSA for 1 hour at RT with shaking. Membranes were washed 3 times for 20 min in TBS and excess buffer was then removed. ECL substrate (Super Signal West Pico Plus Chemiluminescent Substrate, Thermo #34577) was added to the membrane and blots imaged using a Chemidoc MP Imaging System. Optical density was quantified in Image J using the Gel Analyzer tool.

Behavior:

Within 24 hr of eclosion (0 dpe), flies were transferred to narrow vials containing cornmeal agar media. To blind scorers to genotype, vials were labeled with letter designations and genotypes contained in a separate key. Flies were separated by sex and 2-14 flies were housed per vial. While initially this number was 10-14, attrition to do death in some genotypes resulted in more variable conditions of housing density as the flies aged.Within 12 hr of behavioral testing, flies were transferred to a fresh vial.

To evaluate baseline climbing behavior, we marked each vial with a line 3 cm above the top of the food. Flies were tapped to the bottom of the vial and the number of flies which were above the 3 cm line at the reported intervals (5, 10, 15, 30 and 60s) were evaluated. The percentage of flies for each genotype and time point were calculated and plotted. > 100 flies per genotype were scored for each condition.

Seizure susceptibility was evaluated in flies by vortexing the vial at the max speed setting for 10 s. At the time points reported here, flies rarely exhibited complete sustained paralysis after vortexing, but we did see flies which appeared to exhibit recovery seizures, and, most commonly, a refractory period in which they remained at the bottom of the vial and failed to exhibit their typical anti-geotaxis behavior, scored as previously described[87]. All of these phenotypes were designated as "not recovered" while flies exhibiting normal anti-geotaxis were scored as "recovered". These behaviors were scored 1 min after vortexing.

Survival:

Flies used for survival analysis were collected at 0 dpe and transferred to narrow vials containing cornmeal agar media. Flies were separated by sex and maintained < 14 flies per vial. While initially, there were 10-14 flies present per vial, at terminal time points for some genotypes, there were fewer flies. The number of remaining flies was counted every 2-3 days. Differences in survival curves were compared using log-rank Mantel-Cox tests.

Statistics:

All statistical analyses were performed using GraphPad Prism. All bar graphs are presented as mean +/- SEM and each dot represents one biological replicate (n). Pairwise comparisons were performed using two-way t-tests. One-way ANOVAs were performed to compare results across 3 or more groups and additional posthoc tests performed using Tukey's multiple comparisons tests. Two-way ANOVAs were performed and multiple comparisons made using Fisher's posthoc tests. Normality was assumed across experiments. p values are designated as ns, *$p \geq 0.05$, **$p<0.01$, *** $p<0.001$, and **** $p<0.0001$.

Supplemental information titles and legends:

Figure S1:

(A) Brains from Brp-eGFP-mCherry flies were dissected at 3 dpe and co-stained with the astrocyte marker GAT. (B) TRAPseq was performed on flies at the indicated time points. Ribosomes in astrocytes were labeled with eGFP, GFP antibodies used to pull down these ribosomes and then the associated mRNA's were sequenced. (C) Comparisons were made to identify differentially expressed genes between late pupal and 1-3 dpe astrocytes, (D) 1-3 vs 10-12 dpe astrocytes, and (E) 50-60 vs 10-12 dpe astrocytes.

Figure S2:

(A) Brp-GFP levels were measured from lysates containing between ¼ and 10 fly heads and (B) signal could be readily detected in lysates even from ¼ of a fly head within the linear dynamic range of the assay. (C) ELISAs for Brp-GFP were performed with 20 replicates of control flies and the distribution of results compared between males and females. Male flies exhibited a less variable distribution. (D) 100 combinations of 1-5 samples were drawn from the 20 male control replicate samples and the distribution of these results plotted. Using one replicate resulted in the highest degree of deviation from the true sample mean, while five resulted in the least. We decided using three biological replicates appropriately balanced minimizing variability and required resource use. (E) Flies were collected at 10-12 dpe across the indicated zeitgeber times (ZT) and Brp-GFP levels measured across these samples by ELISA. This was performed in control flies (Brp-GFP alone) or in *per*^{01} mutant flies crossed into the Brp-GFP line. Only males were used in these experiments. (F) Circadian changes in Brp-GFP levels were evaluated in 3 dpe flies across circadian times. (G) 45 of the RNAi lines used in the screen were lethal in the Brp-GFP background when knocked down in all glia with *repo-Gal4*, and so Brp-GFP levels were measured in the remaining 926 lines. (H) A dendrogram of the relationships between the top 30 enriched GO terms in genes that when knocked down increase Brp-GFP levels and (I) that when knocked down in glia decrease Brp-GFP levels. The lowercase roman numerals correspond to the networks shown in Fig 2.

Figure S3:

(A) The mean intensity of Brp-GFP signal was quantified across all neuropil regions in the anterior Drosophila brain at 3 dpe. (B) A *crq-Gal4* line was used as a transcriptional reporter to drive a nuclear-localized mCherry, and glial nuclei were stained with repo. (C) The percent of crq-expressing repo^{+} cells and (D) the percent of repo^{+} cells which were crq^{+} were quantified over time. (E) Brains were stained to visualize neuronal nuclei (elaV) and the nuclei of dying cells (cleaved Dcp1). There were no cleaved Dcp1^{+}elaV^{+} cells identified, but the total number of cleaved Dcp1^{+} cells was quantified.

Figure S4:

(A) Lysosensor was used to visualize lysosomes in acutely dissected live fly brains at 3 dpe; while there was some background from tracheal signal which was excluded from the analysis, individual puncta representing lysosomal signal, as shown in the zoomed images, was quantified within the neuropil. (B) Astrocyte membranes were labeled using the *GMR25H07-Gal4* driver to express *UAS-mCD8::GFP* and representative images from antennal lobes are shown. (C) GFP signal from these genotypes was quantified by ELISA.

Figure S5:

(A) Brp-GFP levels were quantified by ELISA when *drpr* was knocked down in glia at the indicated time points. (B) Brp-GFP expressing flies were dissected at larval (wL3) and pupal (head eversion, ~12hr after puparium formation) stages and (C) the percent Brp-GFP^{+} area quantified. (D) Maxillary palp injuries were performed unilaterally and fly brains were dissected and fixed 7 days after injury. Or85e^{+} neurons which project to the imaged glomerulus were genetically labeled and stained with GFP. (E) The volume of the injured and uninjured glomeruli were assessed. (F) Climbing behavior was quantified in *yw* control and *crq*^{MI12323} mutants and (G) control *repo-Gal4* flies and flies in which *crq* was knocked down in glia.

The percentage of flies that had climbed > 3cm in the time indicated was quantified in >100 flies for each genotype and time point. (H) Survival was recorded in *crq* mutant and *yw* controls and (I) control *repo-Gal4* flies, and flies in which crq was knocked down in glia, in either a w^{1118} or Sh^{5} mutant background.

Table S1: Astrocyte TRAPseq data

Table S2: Screen data

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Figure 1: *Drosophila* use conserved glial mechanisms to regulate synapse development and maintenance across the lifespan

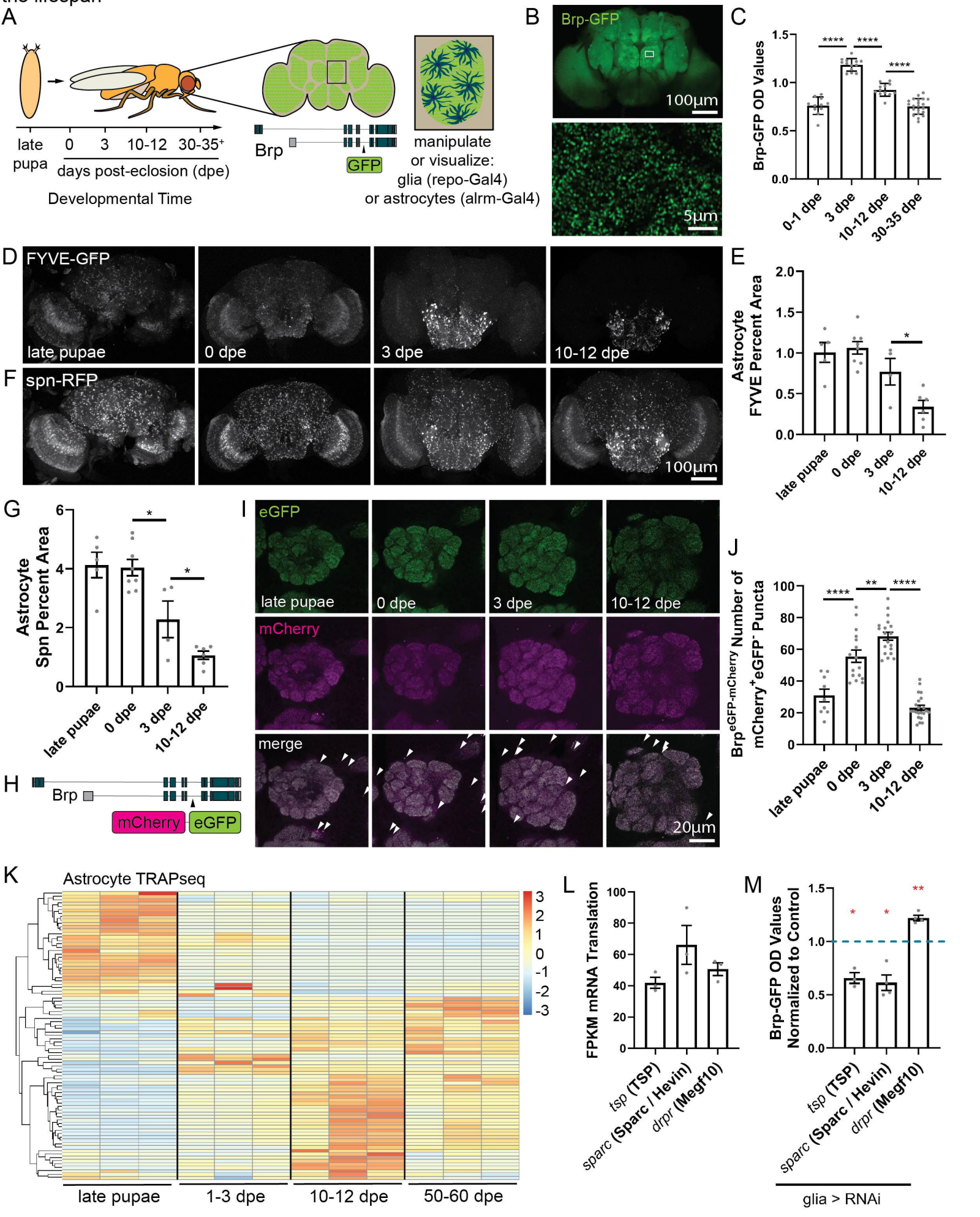


Figure 2: An *in vivo* genetic screen identifies glial regulators of synapse development

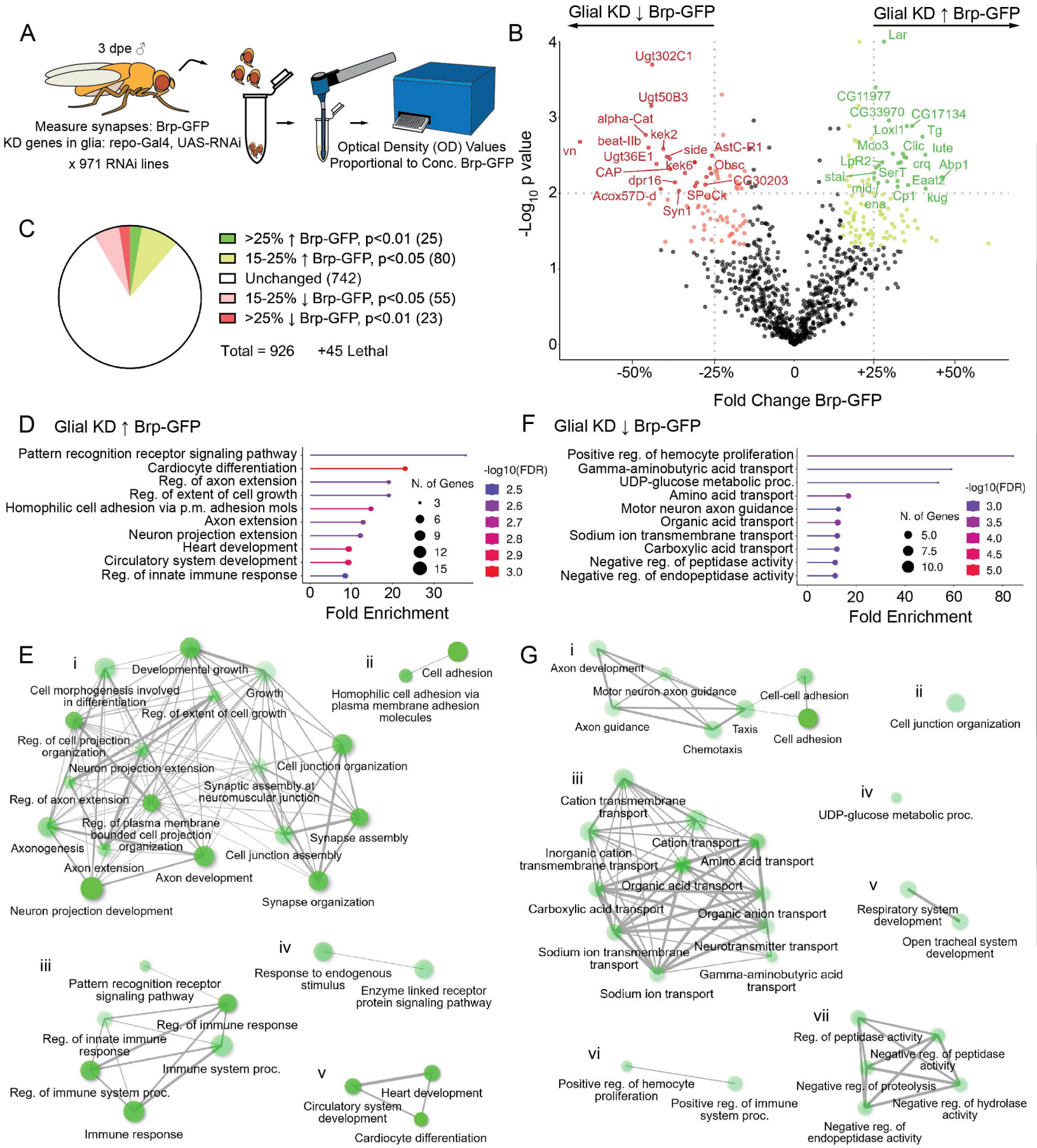


Figure 3: Loss of glial Crq increaes synapse numbers in development

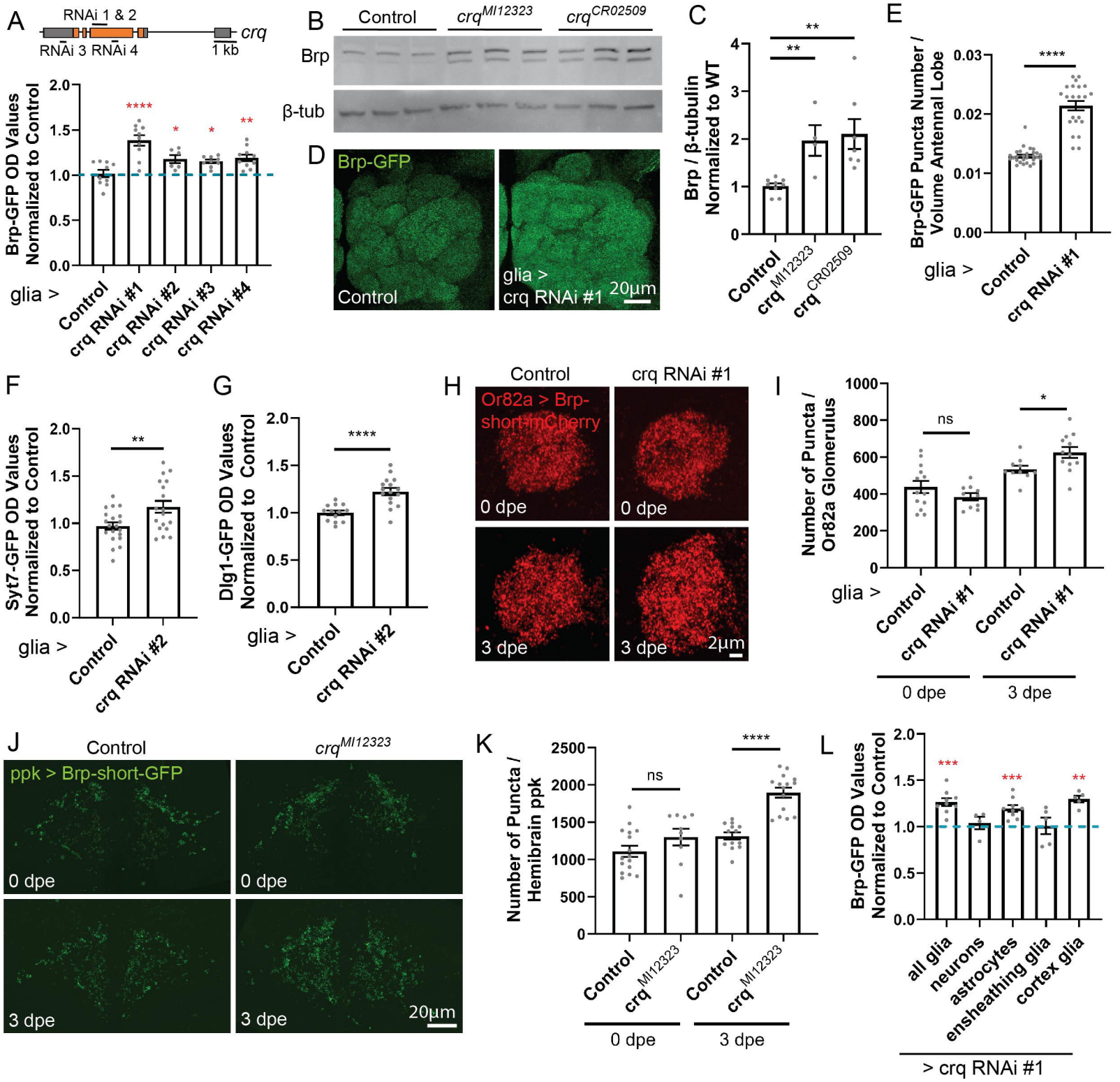


Figure 4: Crq regulates glial synaptic engulfment

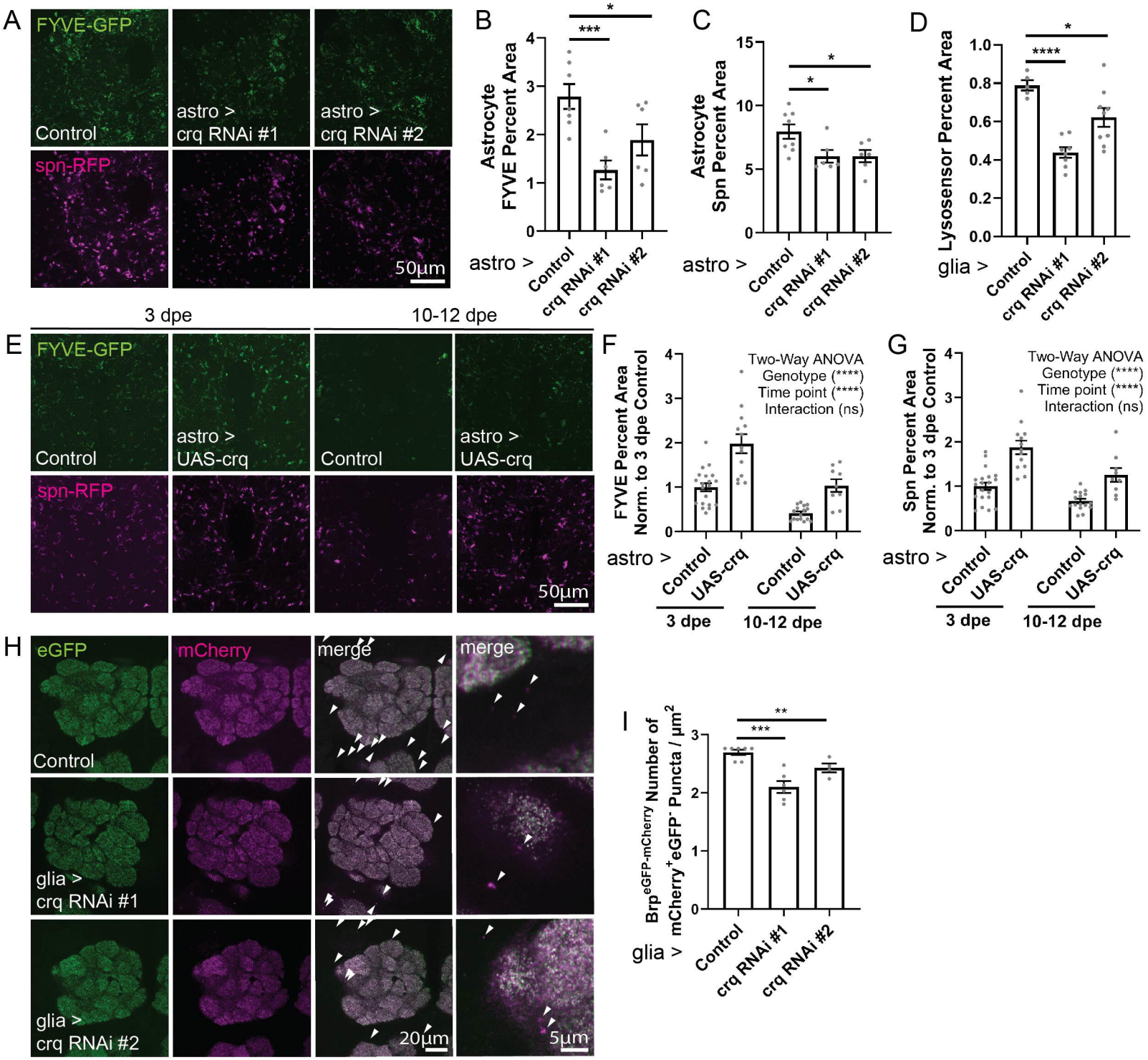
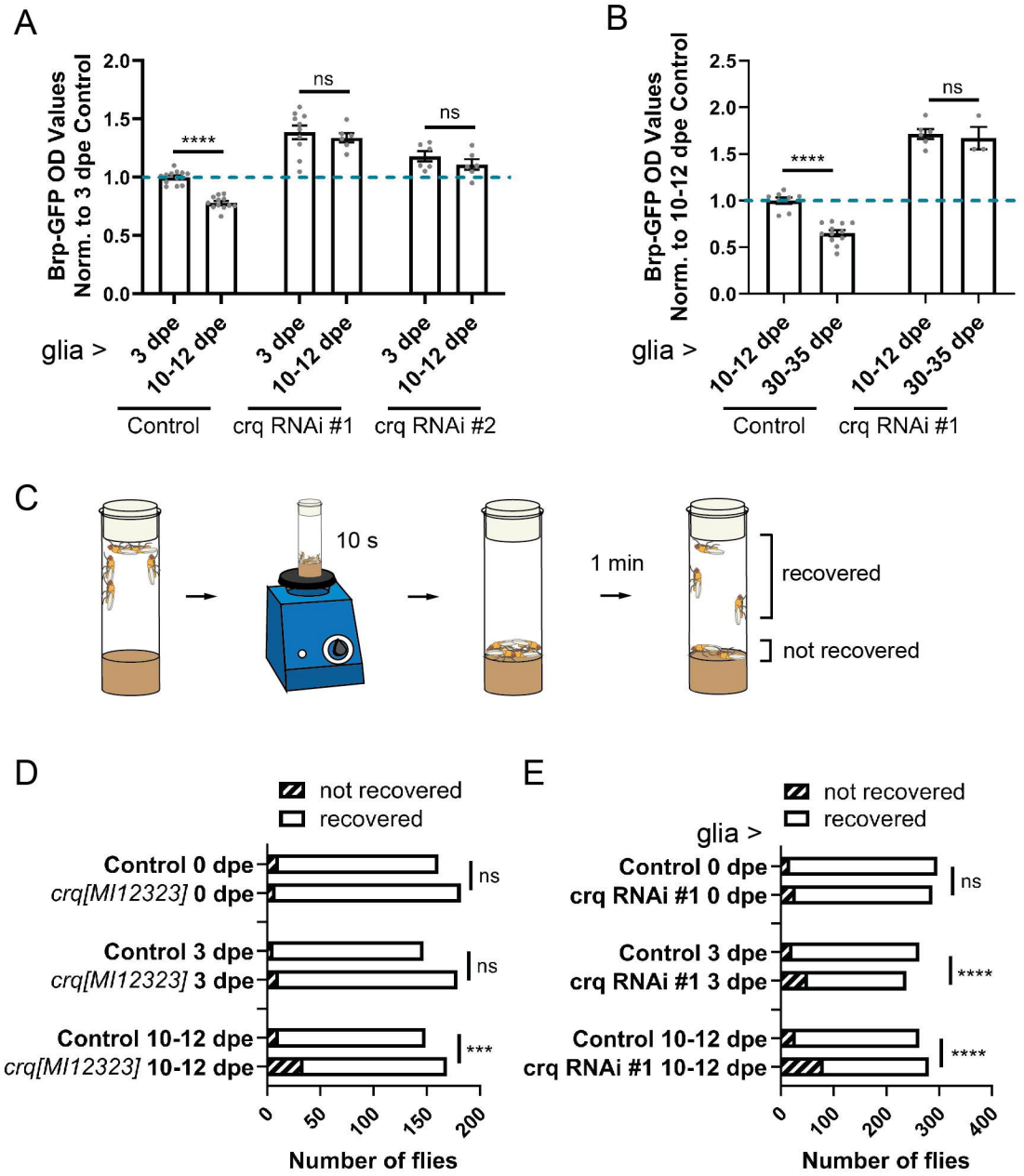
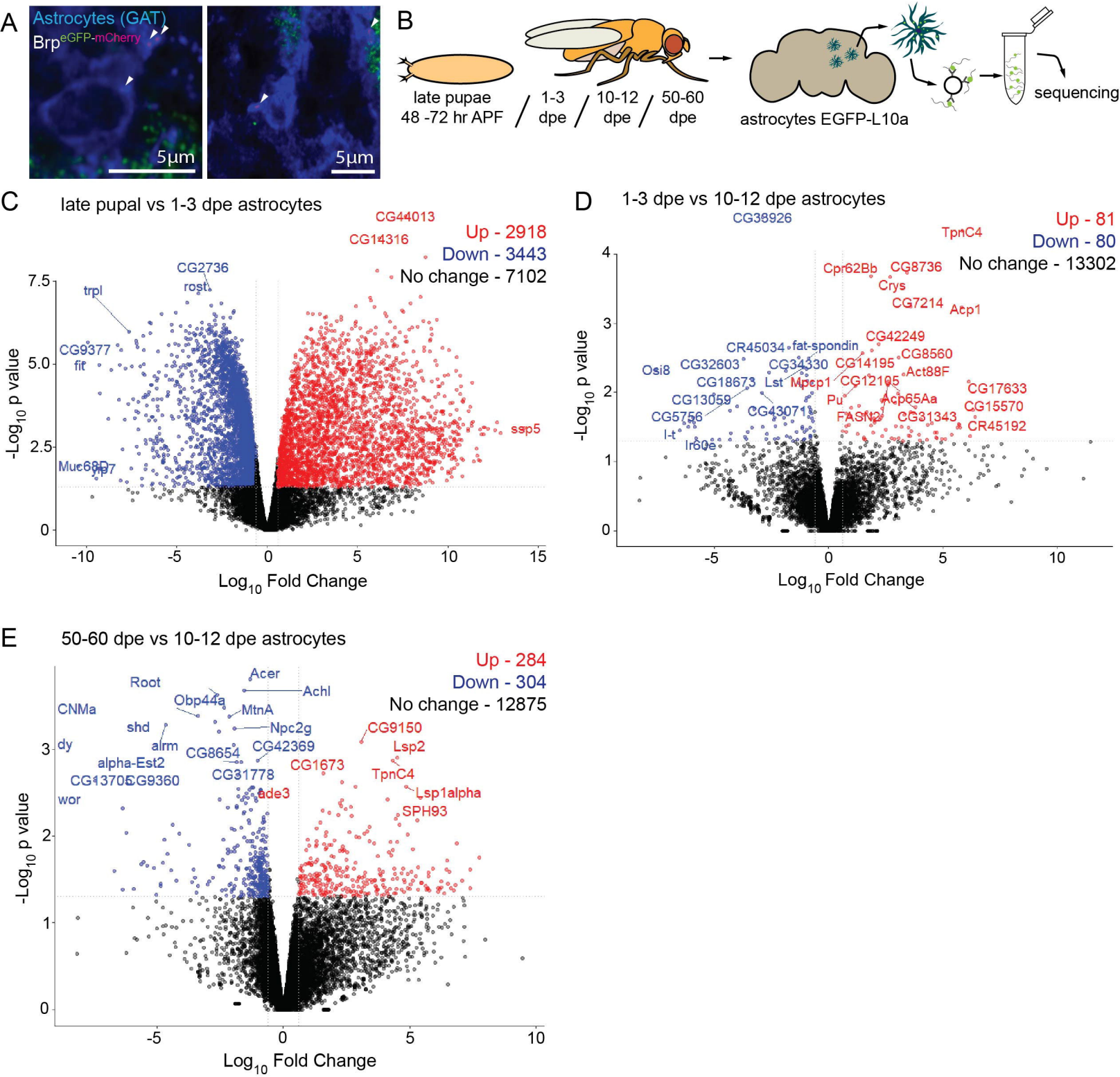


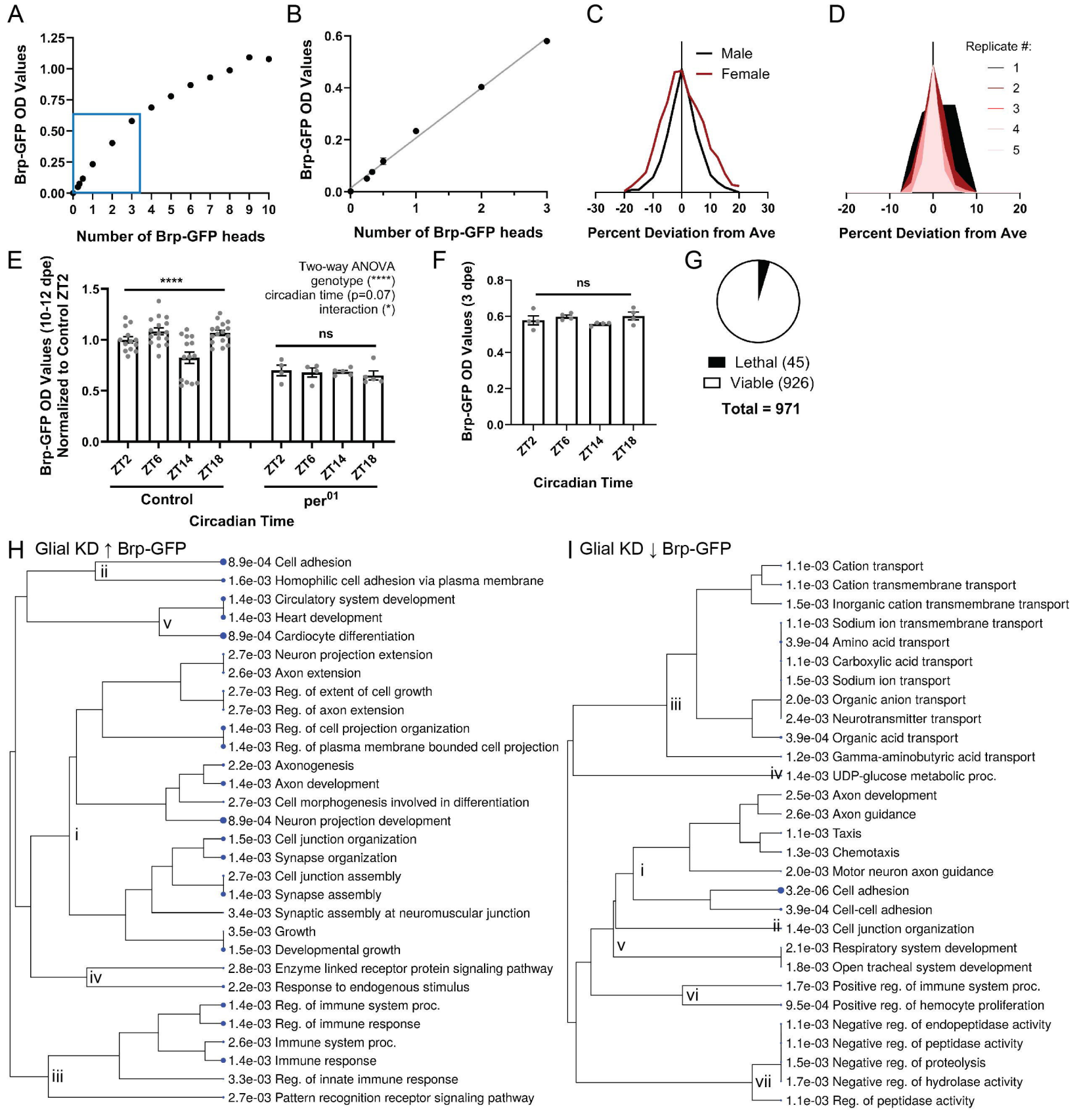
Figure 5: Crq is required for developmental and age-related synapse elimination and proper circuit function



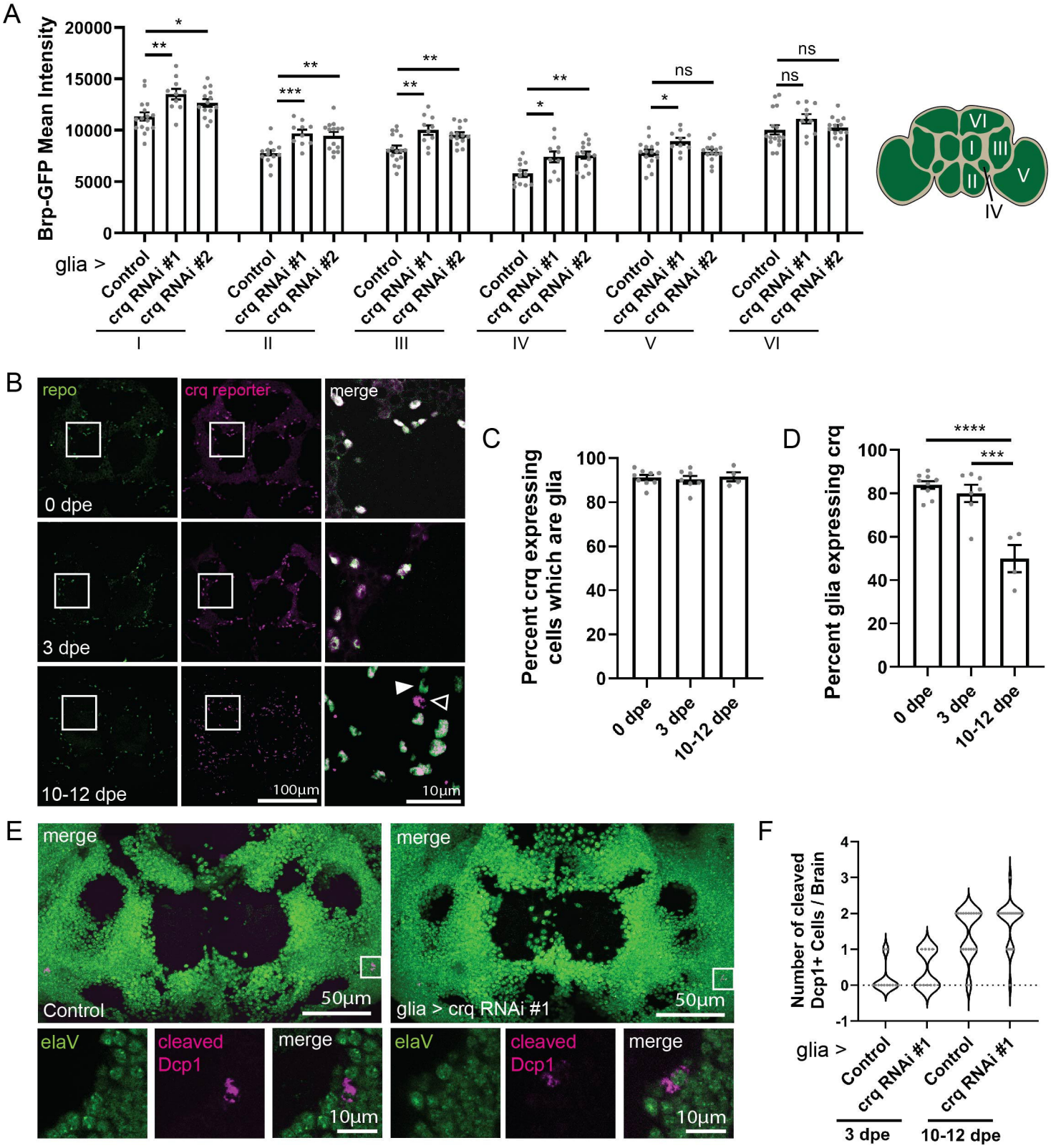
Supplemental Figure 1



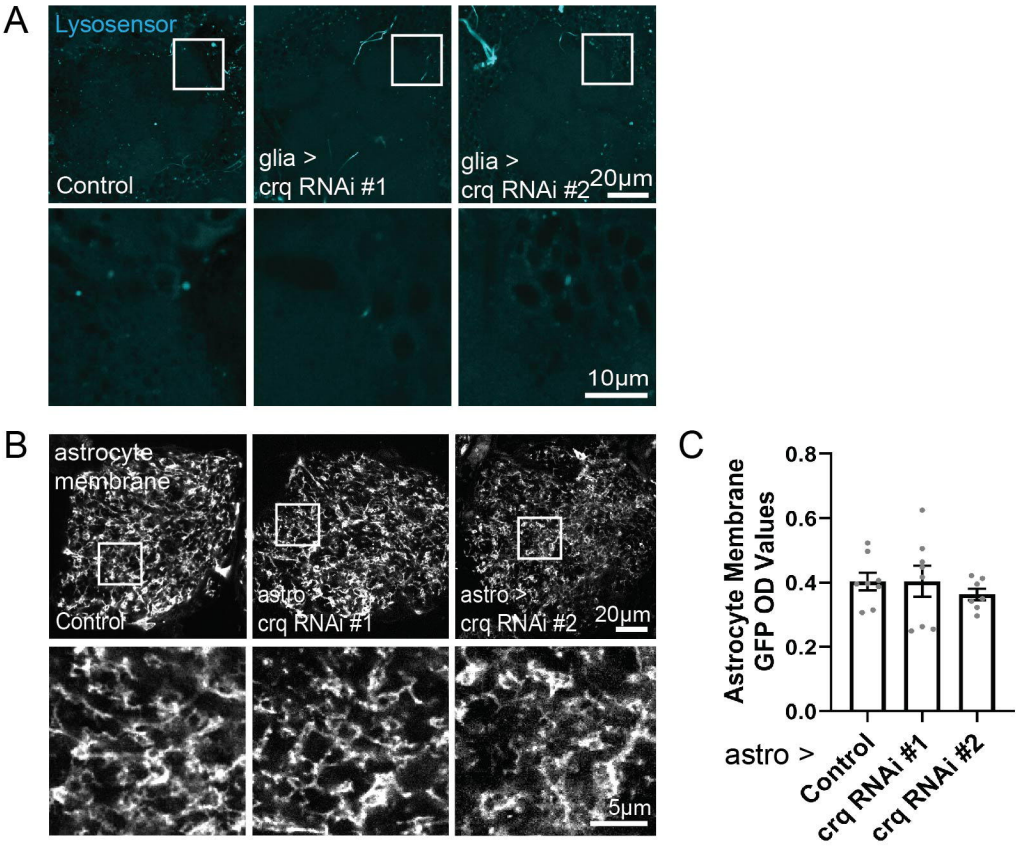
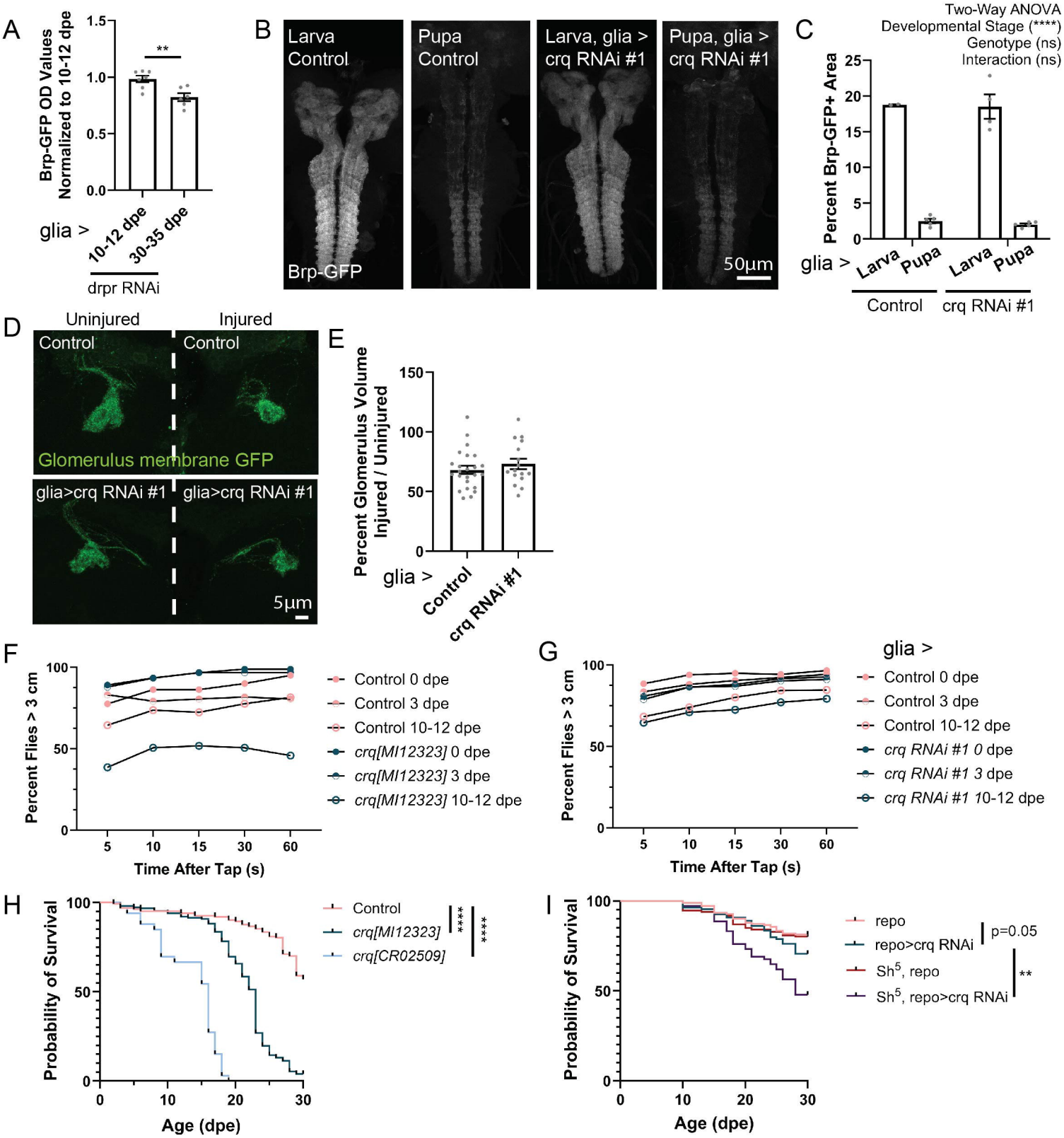
Supplemental Figure 2



Supplemental Figure 3



Supplemental Figure 4



Supplemental Figure 5