Glia are essential components of nervous systems. However, genetic programs promoting glia development and regulating glia-neuron interactions have not been extensively explored. Here we describe transcriptional programs required for development and function of the *C. elegans* cephalic sheath (CEPsh) glia. We demonstrate ventral- and dorsal-restricted roles for the mls-2/Nkx/Hmx and vab-3/Pax6/Pax7 genes, respectively, in CEPsh glia differentiation and expression of the genes hlh-17/Olig and ptr-10/patched-related. Using mls-2 and vab-3 mutants, as well as CEPsh glia-ablated animals, we show that CEPsh glia are important for sensory dendrite extension, axon guidance/branching within the nerve ring, and nerve ring assembly. We demonstrate that UNC-6/Netrin, expressed in ventral CEPsh glia, mediates glia-dependent axon guidance. Our results suggest possible similarities between CEPsh glia development and oligodendrocyte development in vertebrates, and demonstrate that *C. elegans* provides a unique environment for studying glial functions in vivo.

**KEY WORDS:** *C. elegans*, Glia, hlh-17, mls-2, Oligodendrocytes, vab-3

**INTRODUCTION**

Glia, the major cellular components of vertebrate nervous systems, play integral roles in nervous system development and function. For example, glia promote neuronal survival (Hosoya et al., 1995; Jones et al., 1995; Meyer-Franke et al., 1995) and generate directional cues for developing neurons and neurites (Edmondson et al., 1988; Fishell and Hatten, 1991; Serafini et al., 1996; Kidd et al., 1999; Noctor et al., 2001). Glia often ensheath neurons, and recent studies have addressed how oligodendrocytes, the myelinating glia of the vertebrate CNS, are generated (Briscoe et al., 2000; Jessell, 2000). Oligodendrocytes arise from discrete domains in ventral and dorsal regions of the developing spinal cord. Ventrally, the homeodomain transcription factors Nkx6.1/2 and Pax6 (Sun et al., 1998) are required for expression of the basic helix-loop-helix (bHLH) transcription factor Olig2 (Liu et al., 2003; Novitch et al., 2001; Vallstedt et al., 2001). Olig2, together with Olig1, controls neuroepithelial cell commitment to the oligodendrocyte lineage (Lu et al., 2000; Zhou et al., 2000). Genes promoting dorsal expression of Olig2 are unknown, but might include Pax7 (Cai et al., 2005; Fogarty et al., 2005; Vallstedt et al., 2005).

Despite burgeoning interest in glia and their functions, technical challenges in understanding their effects on neuronal activity and development remain. Importantly, because of their neurotrophic functions, glia manipulation often leads to neuronal death, preventing the study of glial contributions to other neuronal activities. Identification of systems in which glia are not required for neuronal viability could allow unprecedented access to understanding glial influences on neurons.

The Caenorhabditis elegans hermaphrodite contains 50 glial cells associated with sensory organs of the animal (Heiman and Shaham, 2007; Shaham, 2006). Although the morphology and anatomy of these glia have been characterized (Ward et al., 1975; White et al., 1986), their functions are not well understood. Of these glia, four cephalic sheath (CEPsh) glia, which associate with cephalic sensory organs of the animal (Heiman and Shaham, 2007), play integral roles in nervous system development and function. For example, glia promote neuronal survival (Hosoya et al., 1995; Jones et al., 1995; Meyer-Franke et al., 1995) and generate directional cues for developing neurons and neurites (Edmondson et al., 1988; Fishell and Hatten, 1991; Serafini et al., 1996; Kidd et al., 1999; Noctor et al., 2001). Glia often ensheath neurons, and recent studies have addressed how oligodendrocytes, the myelinating glia of the vertebrate CNS, are generated (Briscoe et al., 2000; Jessell, 2000). Oligodendrocytes arise from discrete domains in ventral and dorsal regions of the developing spinal cord. Ventrally, the homeodomain transcription factors Nkx6.1/2 and Pax6 (Sun et al., 1998) are required for expression of the basic helix-loop-helix (bHLH) transcription factor Olig2 (Liu et al., 2003; Novitch et al., 2001; Vallstedt et al., 2001). Olig2, together with Olig1, controls neuroepithelial cell commitment to the oligodendrocyte lineage (Lu et al., 2000; Zhou et al., 2000). Genes promoting dorsal expression of Olig2 are unknown, but might include Pax7 (Cai et al., 2005; Fogarty et al., 2005; Vallstedt et al., 2005).

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**MATERIALS AND METHODS**

**Strains**

Strains were handled using standard methods (Brenner, 1974) and were maintained at 20°C, unless otherwise indicated. The wild-type strain used was *C. elegans* var. Bristol (N2). Strain and integrated transgene references are as follows. LGI: *nls105* (hlh-17::GFP); LGIV: *nls136* (ptr-10::myrRFP), *hlh-17* [ns204, ok487 (McMillan and Johnson, 2005)], *hlh-31* (ns217), *hlh-32* (ns223), *sy281* (Fergusson and Horvitz, 1985); LGV: *oyIs17* (gcy-8::GFP) (Satterlee et al., 2001), *oyIs44* (odr-1::RFP) (Lanjuin et al., 2003), *ptr-10* [T08G3.3::RFP] (Lanjuin et al., 2006), *mls-2* (bx23), *vab-3* (ns156, ns158, ns159, cc615) (Jiang et al., 2005); vab-3 [ns157, e648 (Hodgkin, 1983), e1796 (Hedgecock et al., 1987), jn468, sy281, k109, k143 (Cinar and Chisholm, 2004), bx23 (Baer et al., 1991)]; *nsIs108* (ptr-10::myrRFP).
egls1 (dat-1::GFP) (Nass et al., 2005), nls60 (vab-3 promoter::GFP; gift from Andrew Chisholm), zds178 (his-72::H3-GFP) (Ooi et al., 2006) and rns32 (pie-1::H2B-GFP) (Prattis et al., 2001) insertions are unmarked. nT1 qhs3/I; V (Siegfried et al., 2004) was used as a balancer for hll-17 (ok487) and sDf23.

The following extrachromosomal arrays were used: nsEx646 [hll-17::myrGFP + lin15(+)], nsEx725 [hll-31 promoter::RFP + lin15(+)], nsEx729 [hll-32 promoter::RFP + lin15(+)], nsEx1420 [C39E6 + rol-6 (su1006)], nsEx1419 [mls-2 promoter::mls-2 + rol-6 (su1006)], nsEx1404 [F14F3 + rol-6 (su1006)], nsEx1463 [heat-shock promoter::mls-2 + rol-6 (su1006)], nsEx1464 [heat-shock promoter::vab-3 + rol-6 (su1006)], nsEx1577 [mls-2 promoter::vab-3::mls-2 + 3’ UTR + rol-6 (su1006)], nsEx1717 [C39E6 + nhr-38::GFP + elt-2::GFP].

Mutagenesis and mapping

hll-17::GFP animals were mutagenized with 30 mM ethyl methanesulfonate (Solston and Hodgkin, 1998) and plated on 9-cm NGM agar plates. F1 adults were individually plated on 1600 plates and F2 progeny were screened for CEPsh glia defects. Mutants were mapped by crossing to strain CB4856, followed by isolation of homozygous mutant animals and SNP genotyping (Wicks et al., 2001).

Plasmid constructs

hll-31 promoter::RFP

We amplified by PCR a 1.5 kb DNA fragment from cosmids F38C2 containing 1.2 kb sequences upstream of the hll-31 first ATG as well as the coding sequence for the first 32 amino acids. The amplicon was ligated to the RFP gene digested with SpIII and BamHI. No expression was detected for hll-31.

hll-32 promoter::RFP

We amplified a 3 kb DNA fragment upstream of the hll-32 ATG from the YAC Y105C5. The amplicon was ligated to the RFP gene digested with SpIII and BamHI. The hll-32 transgene was expressed in two unidentified neurons in the head.

hll-17::GFP

To define an hll-17 promoter element, we sequenced hll-17 cDNAs and identified some containing the SL1 trans-spliced leader (Krause and Hirsh, 1987), enabling identification of a putative ATG. To generate the reporter we amplified a 2.7 kb DNA fragment from cosmids F38C2 containing 1.9 kb of sequences upstream of the hll-17 ATG and sequences encoding the first 58 amino acids. The 1.9 kb promoter fragment included a 96 bp segment immediately upstream of the ATG. This segment was not present in a transgene previously described (Fig. 1E) (McMiller and Johnson, 2005). The amplicon was ligated to pPD95.69 (Miller et al., 1999) digested with SpIII and BamHI.

hll-17::myrGFP

We amplified a 4 kb DNA fragment from cosmids F38C2 containing sequences upstream of the hll-17 ATG. The amplicon was ligated to the myrGFP gene (Adler et al., 2006) digested with SpIII and BamHI.

ptr-10::myrRFP

We amplified a 300 bp DNA fragment from cosmids F55F8 containing genomic sequence upstream of the ptr-10 ATG. The amplicon was ligated to the myrRFP gene (Adler et al., 2006) digested with SpIII and XmaI.

mls-2 promoter::GFP::mls-2::mls-2 3’ UTR

See Jiang et al. (Jiang et al., 2005).

mls-2 promoter::vab-3::mls-2::mls-2 3’ UTR

vab-3 isoform A cDNA was digested with Sall and ligated into the mls-2 promoter::GFP::mls-2::mls-2 3’ UTR construct digested with Sall, replacing GFP with vab-3.

Heat-shock promoter::mls-2::vab-3

mls-2::vab-3 isoform A cDNAs were digested with AgeI and EcoRI and ligated into the same sites of vector pPD95.75 (Miller et al., 1999). The heat-shock promoter was amplified from vector pPD49.78 (Fire et al., 1990), digested with SpIII and BamHI, and ligated into the same sites as the cDNA vectors.

8.3 kb C39E6 subclone

We amplified an 8.3 kb DNA fragment from cosmids C39E6 containing 5.5 kb of sequences upstream of the mls-2 ATG, the mls-2 coding sequence, and 300 bp downstream of the mls-2 stop codon. The amplicon was digested with PvuI and EcoRI and ligated into the same sites of pPD95.75.

Transgenic strains

Germline transformations were carried out as published (Mello and Fire, 1995). hll-17::GFP (30 ng/μl) and ptr-10::myrRFP (3 ng/μl) were injected into N2 animals. ptr-10::myrRFP (50 ng/μl) was injected into lin-15(765) animals with plasmid pJM23 (20 ng/μl) containing lin-15 (Huang et al., 1994). Extrachromosomal transgenoses were integrated using 4.5’ 8-trimethylpsoralsen followed by insertion homoygote identification (Yandell et al., 1994).

For mls-2 rescue experiments, cosmids C39E6 and its 8.3 kb subclone were injected into mls-2(n156) animals (1 ng/μl). For vab-3 rescue experiments, cosmids F14F3 or a 24 kb Ascl-Pmel subclone were injected into vab-3(n157) animals (1 ng/μl). The mls-2 promoter::vab-3::mls-2::mls-2 3’ UTR construct was injected into N2 animals with plasmid pRf4 (40 ng/μl) containing the dominant marker rol-6 (su1006) (Mello et al., 1991) (20 ng/μl). Other reporter constructs were injected into animals at 30-50 ng/μl with either pRf4, pJM23 or elt-2::GFP (Fukushige et al., 1998) as expression markers (30-40 ng/μl).

Ablations

Strains used for ablation contained either hll-17::GFP or ptr-10::myrRFP together with a neuronal marker to facilitate scoring of CEPsh glia fate and axonal defects. In some cases, ablated strains contained unc-19::GFP (Maduro and Pilgrim, 1995). Precursor cells of CEPsh glia were ablated in embryos at the 250-300 minute stage in a drop of S-basal buffer on 5% agar pads using a micropoint laser set up (Bargmann and Avery, 1995). These cells were identified by following the cell division patterns of embryos (Solston et al., 1983). Ablations were scored as successful if CEPsh glia were absent 2 days later.

Isolation of deletion mutants

Deletion alleles were isolated using published methods (Jansen et al., 1997; Hess et al., 2004). The following first pair primes (5’ to 3’) were used for screening: hll-17::poison primer, GCATGACTAAGAGGACACTTGAC; outer primers, ATGGGGTCCCTGGGACTCT and CGGATTCTCCGAATCGGG; inner primers, TCCCTG-GGACTCCTCCCTG and CGATTTTTCTGCTAATTGGGCACACAC. hll-31: poison primer, GCATGACTTTAAAGGAGCCTGACCTGAC; outer primers, CAGTCCGGATGGAATGAACAAAAGGG and CTACATG-TGCGCCTTGATGCTC; inner primers, TGCAGCGCAATCTAAAGTGGGTC and GGGCAGACATACACTGACCT. hll-32: poison primer, GCATGACCTAAGAGGACACTG; outer primers, GCTTCGTAAGTCTCAAGGC and CTAACTCTCTCGATTGGTGTTGAGGC; inner primers, GCTTCCGTTTTGGGAAACAGG and CTTAGCTCTTCATGTTTGGCCT.

cDNA isolation

cDNAs for hll-17, hll-31, hll-32, mls-2 and vab-3 were isolated by amplification using PCR of a plasmid-based cDNA library (Schumacher et al., 2005) using primers within the vector and within the genes.

Mosaic analyses

C39E6, nhr-38::GFP and elt-2::GFP were co-injected at 1 ng/μl, 50 ng/μl and 20 ng/μl, respectively, into a strain of genotype nls105 (hll-17::GFP); nls145 (tx-1::RFP); mls-2(n156). Animals harboring the extrachromosomal array were selected using elt-2::GFP expression under a fluorescence dissecting microscope, mounted for observation on a compound microscope in M9 medium, and assessed for appearance of hll-17::GFP and nhr-38::GFP expression in the ventral CEPsh glia and AFD neurons, respectively. Similar studies were performed for vab-3 mosaic studies, except that the vab-3 cosmids, F14F3, was injected together with ptr-10::myrRFP into vab-3(n157) mutants carrying an integrated hll-17::GFP reporter, and animals lacking hll-17::GFP expression in subsets of CEPsh glia were examined.

For the unc-6 mosaic studies, we used an elt-2::GFP reporter (Fukushige et al., 1998) to follow transgenic animals.
Microscopy
Animals were examined by epifluorescence using either a fluorescence dissecting microscope (Leica), an Axioplan II compound microscope (Zeiss), or a spinning disc confocal microscope (Zeiss) equipped with a Perkin-Elmer UltraView spinning disc confocal head. For the compound microscope, images were captured using an AxioCam CCD camera (Zeiss) and analyzed using the Axiovision software (Zeiss). For the spinning disc confocal microscope, images were captured using an EMCCD (C9100-12) gain camera (Hamamatsu) and analyzed using MetaMorph software (UIC). Electron microscopy was carried out on serial sections as previously described (Perens and Shaham, 2005).

Heat-shock studies
Heat-shock constructs were injected at 20 ng/μl with pRF4 (40 ng/μl) as the transformation marker. Animals were placed at 34°C for 30 minutes, allowed to recover at 20°C, and scored for induction of reporters 60-150 minutes later.

Southern hybridizations
Preparation of genomic DNA, agarose gel electrophoresis and Southern blotting were performed using standard techniques (Ausubel et al., 1989). Probes were prepared from hlh-17 cDNA by PCR.

Lineage analysis
Lineage tracing was performed essentially as described by Murray et al. (Murray et al., 2006). Three-dimensional time-lapse image series were collected for wild-type (n = 2), mls-2(ns156) (n = 4) and vab-3(ns157) (n = 4) embryos carrying a nuclear-localized his-72::H3.3-GFP reporter using a Zeiss LSM510 confocal microscope. We used StarryNite (Bao et al., 2006) to automatically trace the lineage from the images, and AceTree (Boyle et al., 2006) to identify and edit errors in the StarryNite annotations. Lineages were followed through the 350-cell stage and the CEPsh-producing lineages (ABarp, ABplpaa, ABprpaa) selectively traced through the birth of the CEPsh glia. Because StarryNite makes significantly more errors at and beyond the 350-cell stage than it does at earlier stages, we followed each cell by eye in each lineage throughout its lifespan and corrected all errors. Tree displays and 3D projections were generated in AceTree.

RESULTS
hlh-17/Olig-related and ptr-10/Patched-related are expressed in CEPsh and other glia
To investigate the roles of CEPsh glia in C. elegans nervous system development, we sought to identify reporters that would allow us to visualize these cells. We used two approaches. First, we surmised that C. elegans genes similar to known vertebrate regulators of glial cell fate might be expressed in C. elegans glia. In vertebrates, Olig2 encodes a bHLH transcription factor involved in oligodendrocyte and motoneuron development (Lu et al., 2002; Lu et al., 2000; Takebayashi et al., 2002; Zhou and Anderson, 2002; Zhou et al., 2000). Comparison of the Olig2 protein sequence to predicted C. elegans proteins using BLAST (Altschul et al., 1990) revealed three genes, hlh-17, hlh-31 and hlh-32, situated within a 140 kb region of chromosome IV, encoding proteins exhibiting similarity to the bHLH domain of Olig2 (71, 59 and 71% identity, respectively; Fig. 1D; see Fig. S5A in the supplementary material). To determine whether these genes are expressed in glia, we generated animals carrying transgenes in which promoter regions of each gene were placed upstream of either GFP or the monomeric/multimeric Discosoma Red reporter genes (RFP/DSRed; see Fig. S5E in the supplementary material). Although neither the hlh-31 nor hlh-32 reporter transgene was expressed in glia (see Materials and methods), a transgene, containing 1.9 kb of sequence upstream of the hlh-17 translation start site and 0.8 kb downstream of the start site fused to GFP, was expressed strongly in CEPsh glia at all developmental stages (Fig. 1F) (McMillan and Johnson, 2005) and in some motoneurons of the ventral cord in larvae (see Fig. S1 in the supplementary material). This expression pattern is reminiscent of Olig2 expression in oligodendrocyte and motoneuron lineages (Lu et al., 2000; Zhou et al., 2000).

As a second approach to identify CEPsh glia reporters, we turned to our previous studies demonstrating that DAF-6 protein, which is related to the Hedgehog receptor Patched, is expressed in glia of amphid and phasmid sensory organs (Perens and Shaham, 2005). C. elegans encodes 24 Patched-related proteins (Kuwabara and Labouesse, 2002; Kuwabara et al., 2000) and we hypothesized that some might be expressed in CEPsh glia. We found that a myristoylated RFP, under the control of a 300 bp ptr-10 promoter fragment, was expressed in CEPsh glia (Fig. 1G,H) and in sheath and socket glia of inner and outer labial sensilla, and of the deirid (see Fig. S1G-L in the supplementary material).

CEPsh glia are important for CEP neuron dendrite extension
The availability of CEPsh glia reporters allowed us to explore the functions of these cells during nervous system development. For example, the association of CEPsh glial processes with CEP neuron denticritic processes (Fig. 1A) suggests that blocking CEPsh glia formation might result in CEP denticritic defects. To test this, we ablated direct precursors of CEPsh glia in animals carrying either hlh-17::GFP or ptr-10::myrRFP reporters using a laser microbeam, confirming ablations by the absence of reporter expression. Importantly, we never observed neuronal death following ablations: 205/206 operated animals examined in the studies described in this paper showed normal neuronal marker expression.

We found that 4/4 animals in which the ventral left CEPsh glia precursor, ABplpaaapp, was ablated, had shortened ventral left CEP neuron dendrites, as assessed by expression of the CEP neuron reporter dat-1::GFP (Nass et al., 2005). Similarly, 4/4 animals in which the dorsal left CEPsh glia precursor, ABarpaaaapp, was ablated, displayed shortened dorsal left CEP dendrites (Fig. 2), suggesting that CEPsh glia are important for CEP neuron denticrite extension.

CEPsh glia also control axon guidance and branching in the nerve ring
CEPsh glia also associate with the nerve ring and ventral ganglion (White et al., 1986). To confirm ablations by the absence of reporter expression. Importantly, we never observed neuronal death following ablations: 205/206 operated animals examined in the studies described in this paper showed normal neuronal marker expression.

To assess the effects of CEPsh glia on the development of these axons, we ablated ventral CEPsh glia precursors in animals carrying the reporters odr-1::RFP [AWC (L’Etoile and Bargmann 2000)], ttx-1::DsRed [ADF (Satterlee et al., 2001)] or T08G3.3::RFP [ADF (Sagasti et al., 1999)]. Whereas the axon shapes and lengths of the three neurons are highly regular in wild-type animals, we observed multiple defects in these neurites in operated animals, ranging from a lack of ventrally directed processes to abnormal branching. Major defect classes are depicted in Fig. 3A-H. Defects were more pronounced for AWC and ADF axons than for ADF axons (Fig. 3I). Guidance and branching defects of these neurons were generally observed when ventral, but not dorsal, CEPsh glia precursors were ablated (Fig. 3I).

Taken together, these studies demonstrate that CEPsh glia play spatially restricted roles in axon guidance within the nerve ring. Importantly, these guidance roles appear to be neuron specific.
One explanation for the differential effects of ventral CEPsh glia on different axons is that at certain points within the nerve ring and ventral ganglion, some axons are closer to ventral CEPsh glia processes than others. To determine whether such regions of the nerve ring exist, we examined previous electron microscopy (EM) reconstructions of the nerve ring (White et al., 1986). Indeed, axons of the AWC and AFD neurons are situated adjacent to CEPsh glia processes at two different locations along their lengths, on the outer surfaces of the nerve ring and ventral ganglion (see Fig. S2 in the supplementary material). By contrast, ADF axons are distal to CEPsh glia processes. These observations suggest that short-range signals from CEPsh glia to specific axons might determine axon guidance and branching decisions.

**UNC-6/Netrin mediates glia-dependent axon guidance**

One possible axon guidance cue expressed by CEPsh glia is the *C. elegans* Netrin protein UNC-6, which is expressed in ventral but not dorsal CEPsh glia (Wadsworth et al., 1996). To determine whether UNC-6 mediates CEPsh glia-dependent axon guidance, we first examined the effects of a strong loss-of-function mutation in *unc-6(ev400)* on AWC axon guidance. Fifty-four of 102 animals displayed guidance defects in at least one of the two bilateral AWC axons, suggesting roles for *unc-6* in AWC axon guidance.

To determine in which cells *unc-6* functions for AWC axon guidance, we generated *unc-6(ev400)* animals containing an integrated AWC reporter and an unstable extrachromosomal array consisting of *hlh-17::GFP* and plasmid ΔpSM containing a rescuing *unc-6* gene (Colón-Ramos et al., 2007). Twenty-four out of 25 animals expressing *hlh-17::GFP* in ventral CEPsh glia had normal axon outgrowth. By contrast, 12/23 animals expressing *hlh-17::GFP* in dorsal but not ventral CEPsh glia had normal axon outgrowth, similar to animals lacking *unc-6*. These results, together with the *unc-6* expression pattern, strongly suggest that UNC-6 functions within ventral CEPsh glia to control AWC axon guidance.

**CEPsh glia may control nerve ring assembly**

During our ablation studies, we noticed that 17/91 animals in which ventral CEPsh glia were ablated arrested development in the L1 larval stage. L1 arrest was not observed in mock-ablated animals and...
of all CEPsh glia in L1 animals does not affect nerve ring structure or axon guidance in adults (n=120; M. Katz, S.Y. and S.S., unpublished).

These results suggest that CEPsh glia might be important not only for the guidance and branching of specific axons within the nerve ring, but also for the assembly of the entire structure.

The development of ventral and dorsal CEPsh glia are molecularly distinguishable

To understand the molecular basis of CEPsh glia development, we sought to identify mutants with defects similar to those of CEPsh glia-ablated animals. We mutagenized animals carrying an integrated hlx-17::GFP reporter and scanned F2 progeny for alterations in reporter expression.

Four mutants we isolated form two complementation groups consisting of the three alleles ns156, ns158, ns159, and the single allele ns157, and had reciprocal effects on ventral and dorsal CEPsh glia development (Fig. 1F-N). As shown in Fig. 4, most ns156 (as well as ns158 and ns159) animals lacked expression of hlx-17::GFP and ptr-10::myrRFP in ventral CEPsh glia, whereas reporter expression was usually maintained in dorsal CEPsh glia. Reciprocally, most ns157 animals lacked hlx-17::GFP and ptr-10::myrRFP expression in dorsal CEPsh glia, whereas nearly half expressed these reporters in ventral CEPsh glia. Expression of reporter genes in at least some cells other than the CEPsh glia was essentially unaffected in these mutants (data not shown). Although defects in reporter transgene expression could be found in all CEPsh glia, the dorsal/ventral bias in these defects demonstrates that despite morphological similarities, the development of dorsal and ventral CEPsh glia are molecularly distinguishable.

CEPsh glia are abnormal in ns156 and ns157 mutants

The absence of reporter transgene expression in ns156 and ns157 mutants could reflect defects in either CEPsh glia fate specification or generation. To distinguish between these possibilities, we used automated 4D lineage tracking (Bao et al., 2006) to follow cell divisions leading to CEPsh glia generation in ns156 and ns157 mutants. In 4/4 ns156 and 4/4 ns157 animals examined, all CEPsh glia were generated (see Fig. S3 in the supplementary material) and were properly positioned, with the exception of a single anteriorly displaced dorsal CEPsh cell in one ns156 embryo. These results suggest that the ns156 and ns157 mutations do not block CEPsh glia generation and that CEPsh glia precursors are grossly normal. Thus, these mutations probably disrupt CEPsh glia terminal differentiation or fate specification.

To determine whether CEPsh glia features other than reporter expression were perturbed in these mutants, we used EM to examine whether CEPsh glia ensheathed the nerve ring and ventral ganglion leading into the nerve ring. In 2/2 ns157 animals examined, ensheathment was observed (data not shown). However, in 2/2 ns156 animals, ventral ensheathment was absent (see Fig. S4 in the supplementary material). Furthermore, ventral ganglia of both ns156 mutants were disorganized, lacking characteristic bilateral symmetry (see Fig. S4 in the supplementary material). These results suggest that ns156 disrupts CEPsh glia differentiation/specification more severely than ns157.

To further assess CEPsh glia defects in ns156 and ns157 mutants, we examined CEP dendrite extension in these animals. We found that CEP dendrites in these mutants are shorter than in wild-type animals (Fig. 2E,F), although the shortened dendrites still possessed cilia (Fig. 2E), as in CEPsh glia-ablated animals. Consistent with the...
defects in *hlh-17* and *ptr-10* reporter expression, CEP dendritic defects in *ns156* mutants are mostly restricted to ventral dendrites (Fig. 2G). In *ns157* mutants, defects were seen in 20% and 17% of dendrites of dorsal and ventral CEP neurons, respectively (Fig. 2G), consistent with the EM studies suggesting that *ns157* mutants have subtler defects than *ns156* mutants (see Fig. S4 in the supplementary material).

We also examined *ns156* and *ns157* mutants for defects in AWC, AFD and ADF axon guidance. Defects were observed in both mutants (Fig. 3). Major *ns156* defects are depicted in Fig. 3J-Q, and are reminiscent of defects seen in glia-ablated mutants. Similar abnormalities were seen in *ns157* animals. As in CEPsh glia-ablated animals, *ns156* and *ns157* mutants preferentially affect AWC and AFD axon guidance, and have weaker effects on ADF. It is of note that in *ns156* mutants, AFD, and perhaps AWC, guidance is more disrupted than in CEPsh glia-ablated animals (Fig. 3I), suggesting that some of the defects seen in these mutants might be due to abnormalities in cells other than CEPsh glia.

Finally, we also noted that 38% of *ns156* mutants examined (*n*=577) arrest as L1 larvae and display nerve ring assembly defects resembling those seen in CEPsh glia-ablated animals.
Taken together, the studies described above strongly support the notion that the ns156 and ns157 mutations affect genes important for CEPsh glia differentiation. Furthermore, these studies support the idea that CEPsh glia play key roles in regulating axon guidance, nerve ring assembly and CEP dendrite extension.

**mls-2, an Nkx/Hmx-related gene, controls ventral CEPsh glia differentiation**

We used single nucleotide polymorphism (SNP) mapping and transformation rescue to demonstrate that the ns156 mutation disrupts the gene mls-2 (Fig. 5A). Molecular lesions in mls-2 were identified in ns156, ns158 and ns159 mutants (Fig. 5B), and defects similar to those of ns156 mutants were observed in animals carrying the previously reported mls-2(cc615) mutation (Jiang et al., 2005) (Fig. 4). mls-2 encodes a protein with a homeodomain similar to those of HMX/Nkx5 transcriptional regulators, but lacks the HMX motif, [A/S][E/D]LEAA[N/S], located immediately downstream of HMX homeodomains (Fig. 5C) (Wang et al., 2000). Because Nkx proteins are closely related to HMX proteins, but lack the HMX motif, mls-2 might be more appropriately classified as an Nkx superfamily member.

To determine where mls-2 functions to regulate CEPsh glia differentiation, we generated animals carrying a rescuing transgene in which we inserted GFP upstream of mls-2 coding regions in an 8.3 kb mls-2 rescuing genomic fragment (see Fig. S5E in the supplementary material). We found that GFP::mls-2 was expressed in nuclei of the precursor cells of the left and right ventral CEPsh glia, ABplpaap and ABprpaap, respectively (Fig. 5D-J), and probably within CEPsh cells themselves (although the high density of cells in this region precluded reliable identification, and expression was extinguished postembryonically). GFP expression was also detected in the precursors of dorsal CEPsh glia (Fig. 5K-N), consistent with our observations that mls-2 mutants weakly affect hlh-17::GFP and ptr-10::myrRFP expression in these glia (Fig. 4).

To further confirm that mls-2 functions in the CEPsh glia lineage we performed a mosaic analysis aimed at defining the site of mls-2 function in directing AFD axon guidance. We generated mls-2 mutants carrying integrated hlh-17::GFP and tx-1::DsRed reporters to label the CEPsh glia and AFD neurons, respectively. Into these mutants, we introduced the mls-2 rescuing cosmid and the AFD-specific reporter, nhr-38::GFP, both on an unstable extrachromosomal array. Ventral hlh-17::GFP expression presumably indicated the array was present in ventral CEPsh glia (an assumption that gave the most parsimonious interpretation of the data in Fig. 3V). The presence of this array in AFD was scored by nhr-38::GFP expression. As shown in Fig. 3V, when the array was absent from both CEPsh glia and AFD neurons, all animals displayed axon defects. However, when the array was present in both AFD neurons and CEPsh glia, most animals had no axonal defects. The tx-1::DsRed reporter had a weak (10%) effect on AFD axon guidance on its own. These results support the notion that the ns156 axonal defects are caused by the mls-2 lesion.

We then examined animals in which the array was present in one or the other cell type. We found that in 60% of animals in which the array was present in ventral CEPsh glia, but absent from AFD neurons, axon
guidance was rescued. However, if the array was present only in AFD neurons, 23% of animals had wild-type axons, consistent with the idea that mls-2 affects axon guidance non-autonomously and that mls-2 activity resides within the CEPsh glia lineage.

**vab-3, a Pax6/7-related gene, functions in CEPsh glia to regulate glia development**

We used SNP mapping and transformation rescue (Materials and methods) to demonstrate that ns157 disrupts the gene vab-3 (Fig. 6A). vab-3 is the C. elegans gene most similar to the vertebrate Pax6 and Pax7 genes; it encodes two DNA-binding domains—a Paired domain (PD) and a homeodomain (HD)—and generates three transcripts, A, B and C (Chisholm and Horvitz, 1995). We identified a missense mutation within the vab-3 PD in ns157 mutants, confirming identification of the gene (Fig. 6B).

To determine whether vab-3 functions within CEPsh glia to regulate their differentiation, we performed a mosaic analysis. We introduced an extrachromosomal array containing the vab-3 cosmids and ptr-10::myrRFP into vab-3(ns157) mutants carrying an integrated hlh-17::GFP reporter and searched for animals lacking hlh-17::GFP expression. We found a perfect correlation between ptr-10::myrRFP and hlh-17::GFP expression in dorsal CEPsh glia (Fig. 6D). Importantly, we never observed ptr-10::myrRFP expression in CEPsh cells lacking hlh-17::GFP (n=12), consistent with vab-3 functioning within, or in cells closely related to, CEPsh glia to control differentiation.

To confirm the mosaic studies, we inserted a vab-3 isoform A cDNA directly downstream of the 5.5 kb mls-2 promoter in the mls-2 rescuing genomic clone, and introduced this transgene into vab-3(ns157) mutants. The transgene exhibited weak but reproducible rescue of hlh-17 and ptr-10 reporter expression in dorsal CEPsh glia: 18/100 (18%) animals carrying the transgene expressed hlh-17::GFP in both dorsal left and right CEPsh glia, whereas only 3/104 (2.9%) animals without the transgene expressed hlh-17::GFP in these cells.

To further confirm that vab-3 functions in the CEPsh lineage, we took advantage of the observation that vab-3(ns157) mutants show partially penetrant defects in hlh-17::GFP expression in ventral CEPsh glia (Fig. 4). As shown in Fig. 3I, AWC, AFD and ADF axon defects in vab-3(ns157) mutants were more severe if hlh-17::GFP expression was also disrupted in ventral CEPsh glia, consistent with the idea that vab-3 functions in CEPsh glia and that CEPsh glia are required for axon morphogenesis.

**Different VAB-3 domains may regulate hlh-17 and ptr-10 expression in dorsal and ventral CEPsh glia**

Although vab-3(ns157) mutants show a bias towards dorsal defects in reporter transgene expression, the molecular lesion in these animals may not abolish vab-3 function and, thus, the phenotype of vab-3(ns157) animals might not represent the vab-3(null) phenotype. To test this, we examined CEPsh reporter transgene expression in animals homozygous for two vab-3 alleles, e648 and ju468, that eliminate most, if not all, activity of vab-3 isoform A (Fig. 6B) (Chisholm and Horvitz, 1995; Cinar and Chisholm, 2004). We were unable to detect hlh-17::GFP expression in either dorsal or ventral CEPsh glia in these animals (Fig. 4), suggesting that vab-3 is important for differentiation of all CEPsh glia, and that the weaker phenotype of ns157 mutants is due to residual vab-3 function.

The vab-3(ns157) lesion promotes defects preferentially in dorsal CEPsh glia. Interestingly, we found a similar bias in vab-3(k109) PD mutants, suggesting that the PD might have unique roles in these cells (Fig. 4). To uncover the function of the vab-3...
HD, we examined reporter expression in vab-3(e1796) animals containing missense mutations in the VAB-3 HD (Fig. 6B). Although hlh-17 expression was abrogated in both dorsal and ventral CEPsh glia in these animals, we found a surprising ventral bias in the failure to activate ptr-10 expression (Fig. 4). Dorsal CEPsh glia expressing ptr-10::myrRFP but not hlh-17::GFP still possess normal posterior extensions ensheathing the nerve ring, consistent with our EM results (see Fig. S4 in the supplementary material).

These studies suggest two conclusions. First, different domains of VAB-3 may be important for controlling ventral and dorsal CEPsh glia differentiation, suggesting that the VAB-3 targets in
these cells might be different. Second, the differential perturbation of ptr-10 and hlh-17 expression in vab-3(e1796) animals suggests that vab-3 regulates hlh-17 and ptr-10 expression independently.

**hlh-17 cooperates with vab-3 to regulate its own expression**

To determine whether in addition to mls-2 and vab-3, hlh-17 also plays a role in CEPsh glia development, we used trimethylpsoralen mutagenesis to generate an hlh-17 deletion, ns204, removing most of the hBLH domain (Materials and methods; see Fig. SSD in the supplementary material). hlh-17(ns204) mutants do not display obvious developmental defects or CEPsh glia abnormalities, as assessed by hlh-17::GFP and ptr-10::RFP expression, and AFD and AWC axons project normally in these mutants (see Fig. S6 in the supplementary material). Interestingly, however, whereas hlh-17::GFP expression in ventral CEPsh glia is normal in hlh-17(ns204) mutants, GFP expression levels are significantly reduced in hlh-17(ns204); vab-3(ns157) mutants (Table 1). We observed a similar result using a different hlh-17 allele (tm2850; Table 1). We did not observe enhanced defects in ptr-10::RFP expression (see Fig. S7A,B in the supplementary material). These results suggest that hlh-17 functions with vab-3 to regulate its own expression.

hlh-17(ns204); vab-3(ns157) double mutants show no enhancement in axon guidance defects (92/204 defective AWC neurons, compare with Fig. 3J). We, therefore, wondered whether hlh-17 might act redundantly with the hlh-31 and hlh-32 Olig-related genes to control axon guidance. To test this, we generated hlh-32(ns223) hlh-17(ns204) hlh-31(ns217) mutants by mutagenizing hlh-17(ns204) and then hlh-17(ns204) hlh-31(ns217) mutants with trimethylpsoralen (Materials and methods). The mutations we generated delete portions of the hBLH domains of each gene (see Fig. SSC in the supplementary material). Triple mutants are not defective in axon guidance, hlh-17 or ptr-10 expression, or dendrite extension, nor do they enhance the dendritic defects of vab-3(ns157) mutants (see Fig. S7 in the supplementary material). However, we found weak axon guidance defect enhancement in hlh-32(ns223) hlh-17(ns204) hlh-31(ns217); vab-3(ns157) mutants: whereas only 21/100 vab-3(ns157) animals in which ventral CEPsh glia expressed hlh-17::GFP had AWC axonal defects, 22/39 hlh-32(ns223) hlh-17(ns204) hlh-31(ns217); vab-3(ns157) mutants expressing hlh-17::GFP in ventral CEPsh glia had AWC axonal defects. Thus, hlh-17 may function redundantly with hlh-17-related genes to regulate ventral CEPsh glia functions. However, since we could not detect expression of the hlh-17-related genes in CEPsh glia, it is also possible that they control axon guidance in other ways.

Finally, we note that a previous study suggested that the hlh-17(ok487) mutation promotes lethality (McMiller and Johnson, 2005). However, our extensive genetic studies of this mutation suggest that the lethality is not associated with the hlh-17 lesion (data not shown). Furthermore, the ok487 lesion is not a deletion, as previously reported, but an insertion of DNA into the hlh-17 locus (see Fig. SSB in the supplementary material).

**vab-3 but not mls-2 is sufficient to promote hlh-17 transcription**

To determine whether mls-2 and/or vab-3 are sufficient to promote CEPsh gene transcription, we examined whether expression of heat-shock promoter::cDNA transgenes promoted ectopic hlh-17::GFP.ptr-10::myRFP expression. We found that subjecting non-transgenic (n=160) or heat-shock promoter::mls-2 embryos (n>100) to a 30-minute 34°C heat pulse failed to induce reporter expression.

Strikingly, however, hlh-17::GFP (and ptr-10::myRFP, data not shown) was induced within 60 minutes of heat exposure throughout heat-shock promoter::vab-3 embryos (Fig. 6E-H). Induction required a 500 bp vab-3-responsive element immediately upstream of the hlh-17 translation start site (data not shown).

hlh-17::GFP induction was independent of mls-2, as vab-3-induced expression was still evident in mls-2(ns156) mutants (n=160, two lines examined). Furthermore, a heat-shock promoter::vab-3 cDNA transgene was unable to induce ectopic expression of an mls-2 promoter::GFP::vab-3::vab-3 3′ reporter (n=50, two lines observed). Thus, vab-3 is sufficient to induce hlh-17 expression. Furthermore, the rapid appearance of GFP suggests that vab-3 might activate hlh-17 directly.

Surprisingly, we found that mls-2::GFP expression in anterior cells was greatly reduced or absent in 200- to 350-minute vab-3(ns157) embryos (n>100), but was present at wild-type levels at later stages (n>50). VAB-3 protein (detected by antisera), however, was expressed in a grossly wild-type pattern in mls-2(ns156) mutants (data not shown). These results suggest that vab-3 might also activate hlh-17 via mls-2. Such feed-forward loops are common transcriptional motifs (Shen-Orr et al., 2002). Given the minor role of mls-2 in regulating hlh-17 expression in dorsal CEPsh glia, this alternative activation branch might be more important in ventral CEPsh glia (Fig. 7).

**DISCUSSION**

A transcriptional program promoting the development of ensheathing glia in *C. elegans*

The development of the vertebral spinal cord has been extensively studied, and neuronal and glial transcriptional regulators within this structure have been described (Jessell, 2000; Rowitch, 2004; Nicolay et al., 2007). It has been unclear, however, whether similar transcriptional cascades control invertebrate glia development. The studies described here suggest similarities between *C. elegans* CEPsh glia and vertebrate oligodendrocytes. First, although myelin is not present in *C. elegans* (Ward et al., 1975; White et al., 1986), CEPsh glia, like oligodendrocytes, ensheath neuronal processes. Second, CEPsh and other *C. elegans* glia express HLH-17, the *C. elegans* protein most closely related to oligodendrocyte-expressed Olig2.
Third, although all four CEPsh glia express HLH-17 and ensheath neurons, cell lineages giving rise to dorsal and ventral CEPsh glia are unrelated, and these glia have distinct molecular signatures (Wadsworth et al., 1996), as is the case with oligodendrocytes in the ventral and dorsal regions of the vertebrate spinal cord. Fourth, here we show that HLH-17 expression is differentially regulated in dorsal and ventral CEPsh glia, reminiscent of the pattern of Olig2 expression in the vertebrate spinal cord (Fig. 7). HLH-17 expression in ventral CEPsh glia requires the MLS-2 and VAB-3 transcriptional regulators, whereas expression in dorsal CEPsh glia requires mainly VAB-3, and, specifically, the VAB-3 PD. MLS-2 is similar to Nkx superclass proteins and is distantally related to Nkx6, which regulates ventral Olig2 expression in the neural tube. VAB-3 is the C. elegans protein most similar in sequence and domain structure to Pax6, which controls ventral Olig2 expression in vertebrate spinal cords (79% and 93% identity to the human PAX6 PD and HD, respectively), and to Pax7, which may regulate Olig2 expression in the dorsal spinal cord (71% and 65% identity to the PD and HD of human PAX7, respectively; Fig. 6C), although VAB-3 lacks an octapeptide sequence present in Pax7 (Jostes et al., 1990).

Interestingly, in Pax6 mutant mice, oligodendrocyte precursor cell generation is delayed (Sun et al., 1998), suggesting that Pax6 might control Nkx6. We observed a similar relationship between VAB-3 and MLS-2, demonstrating that VAB-3 acts at early time points to control MLS-2 expression.

Together, our results hint at possible similarities between CEPsh glia development in C. elegans and the development of vertebrate oligodendrocytes; however, differences are also notable. Importantly, mice carrying Olig2 mutations have fewer oligodendrocytes than wild-type animals (Zhou and Anderson, 2002), suggesting developmental roles for this gene. However, hlh-17 mutations do not grossly perturb CEPsh glia generation or differentiation. One explanation for this may be redundancy: in vertebrates, Olig2 and Olig1 control oligodendrocyte numbers (Zhou and Anderson, 2002; Lu et al., 2002). We identified two proteins highly related to HLH-17, showing that triple hlh mutants display more penetrant axon guidance defects in a vab-3 mutant background than hlh-17 mutants alone. Although these defects could reflect redundancy in C. elegans Olig gene function, HLH-17 might also be redundant with other factors, or might primarily regulate CEPsh function post-developmentally. The persistence of hlh-17 expression in CEPsh glia throughout adulthood is consistent with this possibility. Olig2 and Olig1 may function in controlling nervous system repair following injury (Ligon et al., 2006) and it is possible that HLH-17 and its relatives also have similar roles.

### C. elegans CEPsh glia control neurite extension and guidance

We showed that ventral CEPsh glia play key roles in axon guidance, attributed at least in part to UNC-6/Netrin expression, which may function as a local cue to regulate guidance. These results might explain previous observations that the shapes of CEPsh glia and RIA neuron axons are correlated (Colón-Ramos et al., 2007). Short-range functions for Netrin-related proteins have been described (Baker et al., 2006), and Netrin is present on the periaxonal myelin of oligodendrocytes in the spinal cord, suggesting that it might serve local adhesive roles in these glia (Manitt et al., 2001).

The idea of UNC-6-directed local axon guidance raises the possibility that synaptogenesis defects recently reported in mutants lacking UNC-6 or its receptor, UNC-40 (Colón-Ramos et al., 2007), might not be due to direct roles in synapse formation, but to subtle neuronal guidance defects. Mosaic analysis, fluorescence imaging and gain-of-function experiments provided correlative evidence that ventral CEPsh glia influence the position of synapses between the AIY and RIA neurons. However, EM studies demonstrating that this correlation is not secondary to local axon positioning roles of CEPsh glia were not performed. Indeed, EM studies of wild-type animals show that ventral CEPsh glia are not apposed to AIY/RIA synapses; rather, glia contact the opposite side of the AIY axon from that where synapses occur. Furthermore, indirect extracellular glial access to these synapses is obstructed (White et al., 1986; see supplementary fig. 1O of Colón-Ramos et al. (Colón-Ramos et al., 2007); Y.L. and S.S., unpublished), suggesting indirect roles for CEPsh glia in synaptogenesis. Definitive resolution of these issues awaits examination of AIY-RIA synapses in animals lacking CEPsh glia, and EM reconstructions of unc-6/unc-40 mutants.

In addition to UNC-6, other axon guidance/branching proteins in the nerve ring are known, including SAX-3/Robo (Zallen et al., 1999), VAB-1/Eph (George et al., 1998; Zallen et al., 1999) and UNC-40/DCC (Chan et al., 1996). Whereas SAX-3 function in peripheral C. elegans neurons is regulated by SLT-1/Slit ligand, the nerve ring defects of sax-3 mutants might reflect redundant interactions of SAX-3 with SLT-1 and a different ligand (Hao et al., 2001). sax-3 defects include anteriorly displaced nerve rings and cell bodies, anterior axon projections, and defects in ventral projections and axon elongation (Zallen et al., 1999). Although most animals lacking ventral CEPsh glia show only axon guidance and branching defects, about 20% arrest development in the L1 stage, exhibiting anteriorly displaced nerve

### Table 1. hlh-17 and vab-3 together regulate hlh-17::GFP expression

<table>
<thead>
<tr>
<th>Genotype*</th>
<th>Compared to†</th>
<th>Intensity of hlh-17::GFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild type</td>
<td>Wild type</td>
<td>12 20 9 41</td>
</tr>
<tr>
<td>hlh-17(ns204)</td>
<td>Wild type</td>
<td>9 28 4 41</td>
</tr>
<tr>
<td>hlh-17(tm2850)</td>
<td>Wild type</td>
<td>9 27 4 40</td>
</tr>
<tr>
<td>hlh-32(ns223) hlh-17(ns204) hlh-31(ns217)</td>
<td>Wild type</td>
<td>10 27 4 41</td>
</tr>
<tr>
<td>vab-3(ns157)</td>
<td>Wild type</td>
<td>4 28 13 45</td>
</tr>
<tr>
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<td>hlh-32(ns223) hlh-17(ns204) hlh-31(ns217); vab-3(ns157)</td>
<td>vab-3(ns157)</td>
<td>0 4 36 40</td>
</tr>
</tbody>
</table>

*All animals also contained a genomically integrated hlh-17::GFP reporter transgene.
†Single animals of the indicated genotype were compared with either single wild-type or single vab-3(ns157) animals containing the same integrated hlh-17::GFP reporter transgene; relative fluorescence intensity levels were compared.
‡This comparison measures the variability of GFP expression within the hlh-17::GFP transgenic line in otherwise wild-type animals.
§This comparison measures the variability of GFP expression within the hlh-17::GFP transgenic line in vab-3(ns157) animals.
rings and cell bodies (Fig. 3). It is possible, therefore, that CEPsh glia also secrete a SAX-3/Robo ligand regulating nerve ring positioning, assembly and axon guidance. The weak penetrance of the sax-3-like defects we observed might reflect our inability to ablate all four CEPsh glia simultaneously.

A unique genetic system for studying glia in vivo

A major obstacle to studying glia and their interactions with neurons has been their trophic support of neurons. Manipulation of glia, in vivo or in vitro, often leads to the death of associated neurons, precluding detailed studies of glial effects on other neuronal functions. One approach to circumvent this difficulty has been to culture neurons with survival factors, examining the consequences of glia re-addition. This approach uncovered roles for glia-secreted cholesterol in neuronal activity (Mauch et al., 2001) and for glia-produced thrombospondin in synapse formation (Christopherson et al., 2005). However, in vivo verification of these studies remains challenging.

Our studies reveal that the C. elegans CEPsh glia, while possessing morphological, functional and molecular similarities to vertebrate glia, differ from their vertebrate counterparts in that they are not required for neuronal survival. This observation has allowed us to explore glial function in vivo and to demonstrate key roles for these cells in dendrite morphological, functional and molecular similarities to vertebrate glia, precluding detailed studies of glial effects on other neuronal functions. One approach to circumvent this difficulty has been to culture neurons with survival factors, examining the consequences of glia re-addition. This approach uncovered roles for glia-secreted cholesterol in neuronal activity (Mauch et al., 2001) and for glia-produced thrombospondin in synapse formation (Christopherson et al., 2005). However, in vivo verification of these studies remains challenging.

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Supplementary material

Supplementary material for this article is available at http://dev.biologists.org/cgi/content/full/135/13/2263/DC1

References


