Drosophila Vps4 promotes Epidermal growth factor receptor signaling independently of its role in receptor degradation

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ABSTRACT

Endocytic trafficking of signaling receptors is an important mechanism for limiting signal duration. Components of the Endosomal Sorting Complexes Required for Transport (ESCRT), which target ubiquitylated receptors to intraluminal vesicles (ILVs) of multivesicular bodies, are thought to terminate signaling by the epidermal growth factor receptor (EGFR) and direct it for lysosomal degradation. In a genetic screen for mutations that affect Drosophila eye development, we identified an allele of Vacuolar protein sorting 4 (Vps4), which encodes an AAA ATPase that interacts with the ESCRT-III complex to drive the final step of ILV formation. Photoreceptors are largely absent from Vps4 mutant clones in the eye disc, and even when cell death is genetically prevented, the mutant R8 photoreceptors that develop fail to recruit surrounding cells to differentiate as R1-R7 photoreceptors. This recruitment requires EGFR signaling, suggesting that loss of Vps4 disrupts the EGFR pathway. In imaginal disc cells mutant for Vps4, EGFR and other receptors accumulate in endosomes and EGFR target genes are not expressed; epistasis experiments place the function of Vps4 at the level of the receptor. Surprisingly, Vps4 is required for EGFR signaling even in the absence of Shibire, the Dynamin that internalizes EGFR from the plasma membrane. In ovarian follicle cells, in contrast, Vps4 does not affect EGFR signaling, although it is still essential for receptor degradation. Taken together, these findings indicate that Vps4 can promote EGFR activity through an endocytosis-independent mechanism.

KEY WORDS: Vps4, Endocytosis, EGF receptor, Dynamin, Signaling

INTRODUCTION

Endocytosis plays a dual role in signaling by many receptors; it is the route that leads to receptor degradation, but it can also alter the level of signaling activity by controlling receptor or ligand processing, recycling, localization or interaction with downstream components (Andersson, 2012; Callejo et al., 2011; Musse et al., 2012; Shilo and Schejter, 2011; Ueno et al., 2011). Activation of many receptors induces their ubiquitylation, internalization into early endosomes, sorting to multivesicular bodies (MVBs), where they are segregated from the cytoplasm, and ultimately lysosomal degradation (Piper and Lehner, 2011). The GTPase Dynamin catalyzes fission of Clathrin-coated endocytic vesicles from the plasma membrane (Schmid and Frolov, 2011). The subsequent sorting process is mediated by the Endosomal Sorting Complexes Required for Transport (ESCRT) machinery (Hanson and Cashikar, 2012). ESCRT-0, which consists of the Hepatocyte growth factor regulated tyrosine kinase substrate (Hrs) and Signal transduction adaptor molecule (Stam) subunits, binds to and clusters ubiquitylated receptors. ESCRT-0 is recruited to endosomal membranes through interactions between Hrs and phosphatidylinositol 3-phosphate. It then recruits the four-subunit ESCRT-I complex, which brings in ESCRT-II, the substrate for assembly of ESCRT-III. The ESCRT-III subunit Vacular protein-sorting-associated protein 32 (Vps32) polymerizes into filaments that interact with Vps24 and Vps2 to deform the endosome membrane and promote budding of cargo-containing intra-luminal vesicles (ILVs) (Henne et al., 2012; Wollert and Hurley, 2010). Vps2 also recruits the ATPase associated with a variety of cellular activities (AAA) protein Vps4, the only energy-utilizing ESCRT component (Hanson and Cashikar, 2012; Raiborg and Stenmark, 2009). Active Vps4 forms a hexameric complex that disassembles ESCRT-III, allowing recycling of its components, and also plays an active role in scission of the vesicle neck (Adell et al., 2014; Cashikar et al., 2014; Lata et al., 2008; Monroe et al., 2014; Mueller et al., 2012). In addition to their endocytic functions, ESCRT proteins, including Vps4, are required for cytokinesis, viral budding, protecting viral genomes from degradation, exosome secretion, receptor shedding on microvesicles, assembly of nuclear pore complexes, cholesterol transport and plasma membrane wound repair (Barajas et al., 2014; Choudhuri et al., 2014; Du et al., 2013; de Gassart et al., 2004; Jimenez et al., 2014; Morita, 2012; Nabhan et al., 2012; Tang, 2012; Webster et al., 2014).

The effect of endocytosis on signaling by the epidermal growth factor receptor (EGFR) is complex. Blocking EGFR internalization by removing Dynamin prevents its degradation, enhancing some downstream signaling events, but other aspects of EGFR signal transduction require an endosomal localization for the receptor (Jones and Rappoport, 2014; Legent et al., 2012; Miura et al., 2008; Teis et al., 2006; Vieira et al., 1996). Internalized EGFR can be either degraded or recycled to the plasma membrane, a choice that depends on the concentration and nature of the ligand, as ligands that remain bound in acidic late endosomes promote more extensive receptor ubiquitylation (Eden et al., 2012; French et al., 1995; Roepstorff et al., 2009; Sigismund et al., 2005). Recycling can alter the distribution of the receptor on the plasma membrane, controlling its exposure to ligands (Assaker et al., 2010; Jékely et al., 2005; Stetak et al., 2006; Vermeer et al., 2003). In Drosophila, EGFR targeted to the degradation pathway remains active on endosomes, as signaling is increased by ESCRT mutations that trap EGFR in the endocytic pathway (Vaccari et al., 2009). However, the transcriptional response in cultured mammalian cells depends primarily on EGFR activity at the plasma membrane (Brankatschk et al., 2012; Sousa et al., 2012). Observed effects on EGFR signaling could vary depending both on the stage at which endocytic sorting is blocked and the cellular context examined (Babst et al., 2000; Bache et al., 2006; Chanut-Delalande et al., 2010; Lloyd et al., 2002; Miura et al., 2008).
In the *Drosophila* retina, EGFR signaling is essential for the differentiation of all photoreceptors except for R8, the first to differentiate in each ommatidium (Freeman, 1996). Adult eye phenotypes thus provide a rapid screen for new regulators of the EGFR pathway (Legent et al., 2012; Miura et al., 2008; Rogniant et al., 2006; Rogniant and Treisman, 2010). Here, we report that a mutation in *Vps4* disrupts EGFR signal transduction as well as the transduction of other signaling pathways. In *Vps4* mutant cells in the eye disc, EGFR accumulates in endosomes but is unable to signal, resulting in the failure of non-R8 photoreceptors to differentiate. Interestingly, removing the Dynamin encoded by *shibire* does not restore EGFR signaling in the absence of *Vps4*, suggesting a new role for *Vps4* upstream of EGFR internalization. *Vps4* mutant ovarian follicle cells accumulate endocytosed EGFR, but show normal expression of EGFR target genes, indicating that defects in EGFR signaling in imaginal discs are not a consequence of its sequestration in the endocytic pathway. Taken together, these results suggest that *Vps4* promotes EGFR activation independently of its effects on endocytosis.

**RESULTS**

**Vps4 is required for R8 survival and R1-R7 differentiation**

In a mosaic screen of the X chromosome (Legent et al., 2012), we recovered a mutation that prevents photoreceptor differentiation. In eye imaginal discs, clones of *3B1* mutant cells showed a cell-autonomous lack of expression of the pan-neuronal marker Elav (Fig. 1A), normally expressed by differentiating photoreceptors (Robinow and White, 1991). Genetic mapping and sequencing revealed that *3B1* was a missense mutation in the *Vps4* gene. *3B1* transforms glutamate 209, which is adjacent to the first central pore motif of the AAA domain (Scott et al., 2005), into a lysine residue (Fig. 1B), a charge reversal that would probably disrupt protein folding. *3B1* failed to complement the lethality of *Vps4*Δ7b, a small deficiency that covers *Vps4* and its flanking sequences (Rodahl et al., 2009a). Expression of an HA-tagged wild-type *Vps4* cDNA in *3B1* clones fully rescued photoreceptor differentiation (Fig. 1C-E). Additionally, 98% (n=106) of hemizygous *3B1* males were rescued to viability by *tubulin-GAL4*-driven ubiquitous expression of UAS-HA::*Vps4*. These results confirm that the phenotypes observed in *3B1* mutants are due to loss of *Vps4* function.

The absence of photoreceptors in *Vps4* mutant clones could be due to either failure of differentiation or cell death. We observed that *Vps4*Δ7b mutant clones in third-instar eye discs underwent massive apoptosis, as indicated by their pyknotic nuclei and high levels of activated effector caspases (Fig. 2A). Both features were largely rescued in the absence of the initiator caspase Dronc (Steller, 2008) (Fig. 2B). Signaling pathways converging on c-Jun N-terminal Kinase (JNK) have been implicated in the regulation of programmed cell death in various contexts (Dhanakaran and Reddy, 2008). As previously reported for *Vps4* RNAi expression (Rodahl et al., 2009a), we found that *Vps4*Δ7b clones misexpressed the JNK transcriptional target *puckered* (*puc*)-lacZ (Martin-Blanco et al., 1998) (supplementary material Fig. S1A). To assess whether ectopic JNK signaling is instructive in photoreceptor cell death, we created clones mutant for both *Vps4* and *hemipterous* (*hep*), which encodes the upstream activating kinase for JNK (Glise et al., 1995). However, removing *hep* did not restore photoreceptor differentiation or prevent caspase activation (supplementary material Fig. S1B-F). Similarly, inhibiting JNK signaling by overexpressing the JNK phosphatase Puc failed to rescue the *Vps4* phenotypes (supplementary material Fig. S1G,H). JNK activity is thus not the primary driver of apoptosis in *Vps4* mutant cells in the eye disc.

The rescue of cell death observed in the absence of Dronc allowed us to examine early markers of photoreceptor differentiation in *Vps4* mutant cells. In each ommatidium, R8, marked by expression of Senseless (Sens) (Frankfort et al., 2001), is the first photoreceptor to differentiate. R8 cells are singled out of an anterior stripe of proneural precursors expressing Atonal (Ato) (Jarman et al., 1993). Only a few Sens-positive R8 cells were observed in anterior regions of *Vps4*Δ7b mutant clones (Fig. 2C). However, preventing cell death by removing Dronc rescued many R8 photoreceptors (Fig. 2D), indicating that *Vps4* is required for R8 survival. R8 induces EGFR transduction of other signaling pathways. In *Vps4* mutant cells, most rescued R8 cells failed to recruit any Elav-positive neighboring cells (Fig. 2E,F). The absence of R1-R7 photoreceptors is thus not a secondary consequence of cell death, but results from a failure to transduce signals from R8.

**Vps4 mutant cells accumulate inactive signaling receptors**

Mutations in *Tumor susceptibility gene 101* (TSG101) of the ESCRT-I complex and *Vps25* of the ESCRT-II complex cause accumulation of the receptor Notch (N), which drives excessive...
signaling was reduced in $Vps4$ mutant cells, as visualized by lower levels of the transcriptional reporter $E(spl)m6-CD2$ (de Celis et al., 1998; Moberg et al., 2005) in the eye disc (Fig. 3C). We also investigated the requirement for $Vps4$ in N signaling during wing development. As $Vps4$ clones in the wing disc survived poorly (supplementary material Fig. S2), we induced them in a $Dronc$ background, and again observed accumulation of N in large puncta (Fig. 3D). In the wing disc, N is activated in a stripe of cells along the dorsal-ventral (D-V) boundary, where it induces the transcription of cut (ct) (de Celis et al., 1996). Ct expression was lost in $Vps4$ clones (Fig. 3E), confirming that, in contrast to more-upstream ESCRT mutants, $Vps4$ promotes N signal transduction.

We next investigated whether other signaling pathways were similarly affected. In the wing disc, Wingless (Wg) secreted from both the D-V boundary and the hinge surrounding the wing pouch acts at a long range to organize wing growth and patterning (Neumann and Cohen, 1997). Like N and Dl, Wg accumulated in large punctate structures in $Vps4$ mutant cells (Fig. 3F). In both the wing and eye discs, Wg only accumulated in mutant cells within or close to its endogenous domain of expression, which is marked by the reporter $wg$-lacZ (Fig. 3H-I). $wg$-lacZ was unaffected by the loss of $Vps4$ (Fig. 3H), indicating that Wg protein accumulation results from internalization into receiving cells rather than increased transcription. $Vps4$ clones showed reduced expression of the Wg target genes sens in the wing disc (Fig. 3G) (Parker et al., 2002) and dachsous-lacZ in the eye disc (Yang et al., 2002) (data not shown), demonstrating that normal Wg signaling requires $Vps4$.

In contrast to the reduction in N and Wg signaling, we observed increased levels of the second messenger phosphorylated Smad (pSmad) (Tanimoto et al., 2000) in $Vps4$ mutant clones near the domain of expression of the Bone Morphogenetic Protein family member Decapentaplegic (Dpp) in the eye disc (Fig. 3J), suggesting that $Vps4$ mutant cells are able to transduce some signals and that, in contrast to its effects on other pathways, $Vps4$ negatively regulates signaling by Dpp. Taken together, our results indicate that unlike more-upstream ESCRT members, $Vps4$ is required for the transduction of several signaling pathways.

$Vps4$ is required for EGFR signaling

The effect of receptor internalization and endocytic processing on EGFR signaling remains controversial. Although some studies have demonstrated that it contributes to signal termination through lysosomal EGFR degradation (Bache et al., 2006; Razi and Futter, 2006), others results argue that it enables receptor signaling from intracellular organelles (Miaczynska et al., 2004; Shilo and Schejter, 2006), other results argue that it enables receptor signaling from intracellular organelles (Miaczynska et al., 2004; Shilo and Schejter, 2006).

$Vps4$ signaling was reduced in $Vps4$ mutant cells, leading to nonautonomous overproliferation (Moberg et al., 2005; Vaccari and Bilder, 2005). Similarly, we found that $Vps4$ mutant cells accumulated very high levels of both N and its ligand Delta (Dl) in punctate structures (Fig. 3A,B). However, unlike the upstream ESCRT mutants $TSG101$ and $Vps25$, N
Intracellular EGFR colocalized with N in punctate structures, many of which also expressed the early endosomal markers Hrs, Rab5 and Syntaxin 7 (Syx7) (Lloyd et al., 2002; Lu and Bilder, 2005; Russell et al., 2012) (Fig. 4D,G,H; supplementary material Fig. S3A). Little colocalization was observed with markers for recycling endosomes (Rab11), the Golgi (Lava lamp; Lva) or secretory vesicles (Sec15) (Langevin et al., 2005; Sisson et al., 2000) (supplementary material Fig. S3B-D), arguing that the EGFR accumulation is in enlarged endosomes, known as class E compartments in yeast (Russell et al., 2012). Consistent with this view, loss of the ESCRT-I subunit TSG101 caused a similar accumulation of EGFR in punctate structures expressing Hrs (supplementary material Fig. S3F).

S2 cells stably expressing the EGFR (D2F cells) have been used to study EGFR signaling mechanisms (Schweitzer et al., 1995). Treatment of these cells with a purified secreted form of the EGFR ligand Spitz (Spi) (Miura et al., 2006) resulted in increased production and secretion of Aos protein (Fig. 4I). However, RNAi-mediated knockdown of Vps4 (supplementary material Fig. S4A) strongly reduced this response (Fig. 4I). Vps4 RNAi also reduced the phosphorylation of the downstream effector MAPK (also known as ERK and Rolled) in cells treated with Spi (supplementary material Fig. S4B). These results indicate that the effect of Vps4 on EGFR signaling is not dependent on the fate or epithelial organization of imaginal disc cells.

**Vps4 acts at the level of EGFR activation**

In order to determine at which step Vps4 influences EGFR signal transduction, we performed epistasis experiments. In the eye disc, Spi secreted by R8 is the primary ligand for EGFR in R1-R7 (Freeman, 1994; Tio et al., 1994). Its binding triggers receptor dimerization and activation by autophosphorylation, and subsequent recruitment of enzymes and adaptor proteins promotes conversion of Ras (also known as Ras85D) into its GTP-bound form. This small GTPase initiates a kinase cascade by activating Raf (also known as Pole hole), which phosphorylates MEK (also known as Dsor1), which in turn phosphorylates MAPK. Phosphorylated MAPK enters the nucleus and phosphorylates specific transcription factors to regulate target gene expression (Shilo, 2003). During eye development, expression of a secreted form of Spi (sSpi) (Schweitzer et al., 1995) or constitutively active forms of EGFR (Queenan et al., 1997) or Ras (Karim and Rubin, 1998) ectopically activates EGFR signaling and promotes the differentiation of extra photoreceptors (Fig. 5A-C). Expression of sSpi did not rescue photoreceptor differentiation in Vps4 mutant cells, although it triggered ectopic photoreceptor
whether restoring signaling downstream of the receptor could rescue eye disc (Halfar et al., 2001; Yang and Baker, 2003), we wondered downstream or at the level of EGFR activation (Fig. 5G).

required in the receiving cell, upstream of Ras activation but Vps4 of mutant cells; although photoreceptors still failed to differentiate cells showed premature differentiation (Fig. 5E), probably due to expression induced within the clone (supplementary material Fig. S5). Expression of activated Ras was sufficient to bypass the requirement for Vps4 in EGFR transduction and promote the differentiation of extra photoreceptors both within and surrounding the clone (Fig. 5F).

Expression of activated Ras in EGFR transduction and promote the differentiation of extra photoreceptors both within and surrounding the clone (Fig. 5F). Similar epistasis experiments in the wing disc, using aos-lacZ to monitor pathway activation, showed that activated EGFR promoted strong ectopic aos expression in wild-type but not Vps4 mutant cells, whereas activated Ras could upregulate aos-lacZ even in the absence of Vps4 (supplementary material Fig. S6). The activity of Vps4 is thus required in the receiving cell, upstream of Ras activation but downstream or at the level of EGFR activation (Fig. 5G).

Given that the EGFR pathway is required for cell survival in the eye disc (Halfar et al., 2001; Yang and Baker, 2003), we wondered whether restoring signaling downstream of the receptor could rescue the cell death observed in Vps4 mutant clones. Indeed, although activated EGFR did not prevent caspase activation in Vps4 cells (Fig. 5H-J), activated Ras abolished apoptosis (Fig. 5K,L). These results demonstrate that, rather than ectopic JNK signaling (supplementary material Fig. S1) (Rodahl et al., 2009a), impaired EGFR signal transduction is the primary reason for the death of Vps4 mutant cells.

**Vps4 functions upstream of EGFR endocytosis**

Because the effect of Vps4 on EGFR signaling was opposite to the negative effect of other ESCRT components (Vaccari et al., 2009) (see supplementary material Fig. S3E), we wanted to test whether Vps4 acted during endocytosis to affect EGFR signaling. We therefore generated double mutant clones for Vps4 and shibire (shi), which encodes Dynamin, a GTPase required to internalize EGFR and other receptors from the plasma membrane (Henriksen et al., 2013; Sousa et al., 2012; Windler and Bilder, 2010). shiC7 mutant cells have enhanced EGFR signaling, leading to increased photoreceptor differentiation (Legent et al., 2012) (Fig. 6A). The ESCRT-0 component Hrs has a positive role in EGFR signaling and photoreceptor differentiation in the eye disc (Miura et al., 2008). As expected, given that Dynamin acts prior to Hrs in endocytosis, shi
mutant cells still showed increased photoreceptor differentiation in Hrs mutant eye discs, although loss of Hrs reduced photoreceptor differentiation in regions wild-type for shi (Miura et al., 2008) (Fig. 6B). Surprisingly, however, shi7C7 Vps43B1 double mutants showed the Vps phenotype of missing photoreceptors and loss of aos-lacZ expression, even in a Dronc background in which cell death was prevented (Fig. 6C,D). Vps4 was similarly epistatic to shi in clones expressing a dominant-negative thermo-sensitive allele of shi (Kitamoto, 2001) (Fig. 6E,F). As the molecular nature of the shi7C7 allele is unknown, we repeated the epistasis analysis with the previously described null allele shiFL54 (Windler and Bilder, 2010). shiFL54 Vps43B1 double mutant cells also failed to differentiate as photoreceptors, although removing shi prevented the endosomal accumulation of EGFR in these cells (Fig. 6G,H). These results are not consistent with an effect of Vps4 only on internalized EGFR, and suggest that Vps4 can influence EGFR function prior to its endocytosis.

One possibility is that Vps4 might promote EGFR trafficking to the plasma membrane. To investigate this, we made use of the ovarian model system, in which the ligand-producing and responding cells can be distinguished. During egg chamber development, the EGFR ligand Gurken (Grk) is secreted from the oocyte and internalized into first posterior and later dorsal anterior follicle cells to specify their fates (Chang et al., 2008; Nilson and Schüpbach, 1998). This internalization requires both shi and Egfr (Chang et al., 2008), indicating that it is mediated by binding to surface EGFR and subsequent endocytosis. We found that clones of follicle cells mutant for Vps4 were still able to internalize Grk, and in fact accumulated abnormally high levels of Grk that colocalized with internalized EGFR in punctate structures (Fig. 7A). EGFR...
must therefore be present on the surface of Vps4 mutant follicle cells, allowing Grk reception. Surprisingly, Vps4 was not required for EGFR signaling in these cells. In this system, EGFR signaling acts by preventing nuclear localization of the transcriptional repressor Capicua (Cic) (Astigarraga et al., 2007). Cic represses the expression of Notch and other receptors. Thus, given the known role for Vps4 and other ESCRT proteins in targeting receptors for lysosomal degradation (Hanson and Cashikar, 2012), EGFR and other receptors accumulate in enlarged endosomes in Vps4 mutant cells. However, this accumulation has distinct effects on their activity; loss of Vps4 reduces EGFR, Notch and Wg signaling, but increases Dpp signaling. The effect on Wg target genes is consistent with previous findings that endocytosis and MVBs promote Wnt signaling by sequestering Glycogen synthase kinase 3 beta (GSK3β), which thought to require endocytosis, because Smads are recruited to the endocytic pathway as central to the function of Vps4 in eye development.

As expected, given the known role for Vps4 and other ESCRT family receptors by the endosomal protein Smad – smad (Rodahl et al., 2009a). However, we found that blocking JNK activity did not prevent cell death or restore photoreceptor differentiation, indicating that JNK is not the primary driver of these effects of Vps4 mutations. In contrast, activating EGFR signaling downstream of the receptor was sufficient to restore survival of R8 cells and differentiation of R1-R7, highlighting this pathway as central to the function of Vps4 in eye development.

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**DISCUSSION**

**Vps4 affects multiple signaling pathways**

We describe here a point mutation that specifically disrupts the function of Drosophila Vps4. A previous study used a deletion allele that unlike our mutation, could not be rescued by a wild-type Vps4 construct, and thus might also disrupt one or both of the neighboring genes (Rodahl et al., 2009a). We confirmed previous findings that loss of Vps4 results in JNK activation and apoptosis (Rodahl et al., 2009a). However, we found that blocking JNK activity did not prevent cell death or restore photoreceptor differentiation, indicating that JNK is not the primary driver of these effects of Vps4 mutations. In contrast, activating EGFR signaling downstream of the receptor was sufficient to restore survival of R8 cells and differentiation of R1-R7, highlighting this pathway as central to the function of Vps4 in eye development.
of the receptor to late endosomes is blocked by loss of the ESCRT-II subunit Vps25 (Thompson et al., 2005) and perhaps also Vps4.

**Vps4 has effects distinct from other ESCRT complex subunits**

*Vps4* mutants differ from previously described ESCRT mutations in their effects on Notch and EGFR signaling. Internalization of these receptors into the ILVs of MVBs segregates their intracellular domains from cytoplasmic effectors and should thus terminate signaling (Piper and Lehner, 2011). This model is consistent with the excessive Notch and EGFR signaling observed in eye and wing discs in the absence of many ESCRT proteins (Aoyama et al., 2013; Moberg et al., 2005; Rodahl et al., 2009b; Thompson et al., 2005; Vaccari and Bilder, 2005; Vaccari et al., 2009). This increased signaling has been attributed to the lack of lysosomal degradation of these receptors and their continued activity on the endosomal membrane.

*Vps4* mutant cells instead show reduced expression of EGFR and Notch target genes, despite endosomal accumulation of the receptors. *Vps4* mutant cells also fail to induce the non-autonomous overgrowth that results from misexpression of the Notch target gene *unpaired* (FlyBase – *outstretched*) in cells mutant for other ESCRT subunits (Thompson et al., 2005; Vaccari and Bilder, 2005). Notch cleavage and signaling is thought to occur in partially acidified endosomes and thus to require progression through the endocytic pathway (Schneider et al., 2013; Vaccari et al., 2010, 2008; Yan et al., 2009). Although EGFR signaling can occur at the plasma membrane (Brankatschk et al., 2012; Legent et al., 2012; Sousa et al., 2012), some studies suggest that receptor progression from early to late endosomes has a positive effect on signaling (Kim et al., 2007; Miura et al., 2008; Teis et al., 2006). Loss of *Vps4* might block endocytosis so late in the process of ILV formation that the intracellular domains of receptors are trapped in nascent ILV buds and no longer have access to the cytoplasm. Alternatively, an early
block in receptor progression through endocytosis due to failure to recycle other ESCRT subunits (Bahst et al., 1998) could reduce signaling.

**Vps4 might contribute to EGFR activation**

Another possible explanation for the effect of Vps4 on EGFR signaling is suggested by our finding that loss of shi function does not restore EGFR signaling to Vps4 mutant cells, even though it blocks receptor accumulation in the endocytic pathway. Dynamin is required to internalize mammalian EGFR by both clathrin-dependent and -independent mechanisms following its activation with all the ligands tested (Henriksen et al., 2013). In the absence of Dynamin, prolonged signaling of EGFR on the plasma membrane should be unaffected by defects in the late stages of endocytosis. The disruption of EGFR signaling by Vps4 in shi mutant cells thus suggests that Vps4 has a role upstream of cell surface EGFR activation that is distinct from its function in endocytic MVBs. This model is supported by our observation that a constitutively active form of EGFR can partially rescue Vps4 mutant cells (Fig 5E). In addition, although Vps4 affects the progression of EGFR and its ligand Grk, as well as Notch, through the endocytic pathway in follicle cells, signaling by both receptors remains intact in these cells, indicating that the two functions of Vps4 are separable.

The mechanism of this new effect of Vps4 is still unknown. As Vps4 mutant clones accumulate high levels of intracellular EGFR, Vps4 is not required for EGFR transcription or translation. Although some studies have implicated ESCRT-III and Vps4 in the plasma membrane (Baldis and Raymond, 2009; Tu et al., 2011; Zheng et al., 2012), although it seems unlikely that this would influence EGFR activation independently of its trafficking. Vps4 is involved in transporting cholesterol to the endoplasmic reticulum (Du et al., 2000), whereas active forms of Spi are localized basolaterally (Futter et al., 1995; Yoshimori et al., 2000). However, the ability of Vps4 mutant follicle cells to internalize Grk indicates that EGFR is present on the plasma membrane of these cells. It is possible that EGFR is trafficked by direct routes in imaginal discs and in follicle cells. Grk is internalized through the apical domain of follicle cells (Tenentzaff et al., 2000), whereas active forms of Spi are localized basolaterally in discs (Steinhauer et al., 2013). A role for Vps4 in targeting the EGFR to the appropriate membrane domain would, however, not explain the requirement for Vps4 in cultured S2 cells, which lack apical-basal polarity. An alternative possibility is that Vps4 affects EGFR activation independently of its trafficking. Vps4 is involved in transporting cholesterol to the endoplasmic reticulum (Du et al., 2013), and could indirectly affect EGFR activation by altering the composition of membrane rafts (Balbis and Posner, 2010). Loss of Vps4 in yeast was recently shown to result in the accumulation of misassembled nuclear pore complexes (Webster et al., 2014); although it seems unlikely that this would influence EGFR activation, it supports the existence of previously undescribed functions for Vps4. Further investigation of the effect of Vps4 on EGFR activity might define a new molecular mechanism of action for this versatile protein.

**MATERIALS AND METHODS**

*Drosophila genetics*

3B1 is an EMS-induced lethal allele of Vps4 isolated previously (Legent et al., 2012). Using rescue by X chromosomal duplications followed by recombination with P-element markers (Zhai et al., 2003), we mapped it to a 0.35 cM interval in 16F1-5. The coding region of Vps4 was amplified from homozygous mutant larvae contained a missense mutation, E209K, that was absent from the y,w, FRT19A isogenic strain used for the mutagenesis. The rescuing duplication Dp(1;3)CI53 (R1) was obtained from Alberto Ferrus (Cajal Institute, Madrid, Spain). hep2- (Gisler et al., 1995) is a deletion of nucleotides 486 to 1346 that removes the start codon. Other stocks used were wg-lacZ, puc-lacZ297, UAS-puc24, Hs528, Df(Hrs) [Exel6277], aos-lacZ, hh-calZ,3000, mirr-lacZ2v2 (Bloomington Drosophila Stock Center), E(sp)65-CD2 (de Celis et al., 1998), pipe-lacZ (Andreu et al., 2012), vps4A (Rodahl et al., 2009a), Dronc(2) (Xu et al., 2005), shi7C7 (Legent et al., 2012), shi (Windler and Bilder, 2010), UAS-shi (Kitamoto, 2001), TSG101 (Moberg et al., 2005), UAS-Rhomboid (Lee et al., 2001), UAS-Spi (Schweitzer et al., 1995), UAS-EGFR29 (Queenan et al., 1997) and UAS-Ras (Karim and Rubin, 1998).

**Stocks used to generate clones**

The full-length Vps4 (CG6842) coding region was amplified by PCR from the GH02678 EST clone (Drosophila Genomics Resource Center) using Pfu Turbo and cloned into pUAST-HA as an EcoRI-Xhol fragment to generate pUAS-HA:Vps4. Transgenic flies were generated by Genetic Services, Inc.

**Immunohistochemistry**

Third-instar eye and wing discs were dissected and stained as described previously (Legent and Treisman, 2008). Ovaries were stained as described previously (Miura et al., 2006). Antibodies used were: rabbit anti-β-galactosidase (1:500, Cappel), chicken anti-GFP (1:500, Aves), mouse anti-α-HA (1:100, Covance), mouse anti-CD2 (1:50, Serotec), rabbit anti-active Caspase 3 (1:500, CM1, BD Pharmingen), rabbit anti-Ato (1:500, Jarman et al., 1993), guinea pig anti-Sens (1:1000; Nolo et al., 2000), mouse anti-NeCD (1:10), mouse anti-DiCD (1:10), mouse anti-Wg (1:50), mouse anti-Ct (1:10), mouse anti-Elav (1:100) (all Developmental Studies Hybridoma Bank, University of Iowa), rabbit anti-EGFR (1:500, Rodrigues et al., 2005), mouse anti-EGFR (1:200, Sigma E2906), rabbit anti-phospho-Smad (1:50, Cell Signaling 9516), guinea pig anti-Hrs (1:200; Lloyd et al., 2002), rabbit anti-Rabs (1:50; Wulczyn et al., 2003), rabbit anti-Rab1 (1:1000; Satoh et al., 2005), chicken anti-Syk7 (1:500; Lu and Bider, 2005), rabbit anti-Lva (1:5000; Sisson et al., 2000), guinea pig anti-Scal (1:500; Mehta et al., 2005), and rabbit anti-Cic (1:5000; Aystigarraga et al., 2007). Secondary antibodies used were from Jackson Immunoresearch Laboratories (1:200) or Molecular Probes (1:1000).

**Cell culture**

EGFR-expressing S2 (D2F) cells (Schweitzer et al., 1995) were maintained in Schneider’s medium supplemented with 10% fetal calf serum and 150 µg/ml G418. Double-stranded RNAs (dsRNAs) were generated using the MEGAscript T7 and T3 Kits (Ambion) as described previously (Roignant et al., 2006) and 15 µg dsRNA were used to treat 10^6 cells per well for 5 days. EGFR expression was induced for 3 h with 60 µM Cu2SO4. For dpERK (pMAPK) western blots, the cells were treated with purified His-sSpiCS for 16 h.

Antibodies used for western blotting were mouse anti-diphosphorylated ERK (dpERK, 1:2500, Sigma M8159), rabbit anti-ERK (1:20,000, Cell Signaling 4695), mouse anti-Aos (1:100, Developmental Studies Hybridoma Bank), and mouse anti-β-Tubulin (1:3000, Covance MMS-410P) antibodies.
Western blotting was carried out as described previously (Murata et al., 2006). Total RNA was extracted from D2F cells using Trizol (Invitrogen). RT-PCR was performed on 1 μg of total RNA using the Invitrogen SuperScript First-Strand Kit. Primer sequences are available on request.

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Competing interests
The authors declare no competing or financial interests.

Author contributions
K.L. and J.E.T. designed experiments; K.L., H.H.L. and J.E.T. performed experiments; K.L. and J.E.T. wrote the manuscript.

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Supplementary material
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References


RESOLUTION ORGAN RESEARCH


Fig. S1. Blocking JNK signaling does not rescue Vps4 differentiation or survival phenotypes. (A-F) Eye discs with mutant clones marked by the absence of GFP (green). (A) Vps4^{3B1} mutant clones express puc-lacZ (A, magenta in A’). (B-C) Vps4^{3B1}, hep^{R75} double mutant clones show no rescue of photoreceptor differentiation. Clones are devoid of Elav (blue in B) and the R8 marker Sens (red in B, blue in C) staining, and show reduced expression of Atonal (Ato, red in C), a marker of proneural precursors. (D-F) Photoreceptors are stained with Elav in blue and activated Caspase 3 is stained in red. hep^{R75} mutant clones (D) do not affect photoreceptor differentiation or survival. The loss of photoreceptors and the cell death
observed in $Vps4^{3B1}$ clones (E) is not rescued in $Vps4^{3B1}$, $hep^{R75}$ double mutant clones (F). (G-H) Eye discs containing clones overexpressing $puc$, marked by coexpression of GFP (green) and stained for Elav (blue) and activated Caspase 3 (red). (G) Expression of $UAS-puc$ alone does not affect photoreceptor differentiation or survival. (H) $Vps4^{3B1}$ clones expressing $UAS-puc$ still show loss of photoreceptors and Caspase activation.
Fig. S2. Vps4 mutant cells in the wing disc undergo apoptosis. (A,B) A third instar wing imaginal disc with Vps4<sup>3B1</sup> clones positively marked by the expression of GFP (green). Mutant clones accumulate activated Caspase 3 (A, magenta in A’) and the receptor N (B, magenta in B’) in punctate structures (arrowheads). Note that accumulation of Caspase- and N-positive structures sometimes predates detectable levels of GFP (filled arrowhead).
Fig. S3. EGFR accumulates in endosomes in Vps4 mutant cells. All panels show eye discs with clones marked by the absence of GFP (green in B, D, E) or RFP (red in A, C, F). (A-D) show Vps4^3B1 clones in a drc mutant background. EGFR (A’, B’, C’, D’, blue in A”, A””, B””, B”’”, C””, C”’”, D””, D”’”) accumulates in punctate structures that colocalize with the early endosomal marker Syx7, also known as Avalanche (Avl) (A, green in A”, A””), but do not show significant colocalization with the recycling endosome marker Rab11 (B, red in B””, B”’”) or the Golgi marker Lva (C, green in C””, C”’”), and only partially colocalize with the exocyst component Sec15 (D, red in D””, D”’”). xz sections are shown below the xy panels. (E, F) show TSG101^2 clones stained for the
EGFR target Sty (E, red in E'', E'''), the photoreceptor marker Elav (E', blue in E'', E'''), the endosomal marker Hrs (F, blue in F'', F''') and EGFR (F', green in F'', F'''). Although loss of TSG101 affects EGFR signaling in the opposite way from loss of Vps4, indicated by increased Sty expression (arrowheads), EGFR is still colocalized with Hrs in endosomes.
Fig. S4. Vps4 is required for normal MAPK phosphorylation in response to Spi. (A) shows RT-PCRs on RNA extracted from lacZ or Vps4 dsRNA-treated D2F cells, as indicated. Vps4 knockdown strongly decreases the amount of Vps4 transcripts but not Vps25 or Vps32 control transcripts. (B) shows Western blots of phospho-MAPK, total MAPK and β-Tubulin from lysates of D2F cells treated with lacZ or Vps4 dsRNAs, as indicated, and exposed (+) or not exposed (-) to purified Spi for 10 min. Vps4 knockdown strongly reduces MAPK phosphorylation in response to Spi.
**Fig. S5.** **EGFR^{act}** restores moderate *hh-lacZ* expression to *Vps4^{3B1}* mutant clones. Eye discs expressing *hh-lacZ* (red), stained for Elav (blue), and carrying GFP (green)-marked clones of cells, either mutant for *Vps4* (A), or expressing *UAS-EGFR^{act}* (B) or both mutant for *Vps4* and expressing ectopic *UAS-EGFR^{act}* (C). (A) Arrowheads point to the loss of *hh-lacZ* and Elav expression in *Vps4* clones. (B) Both markers are ectopically expressed in response to ectopic *EGFR^{act}*, autonomously (asterisks), and in cells surrounding the clones, anterior to the morphogenetic furrow (arrowheads). (C) In *Vps4* clones, ectopic *EGFR^{act}*, restores weak autonomous expression of *hh-lacZ* but not Elav (asterisks), resulting in non-autonomous photoreceptor differentiation (arrowheads).
Fig. S6. *Vps4* acts at the level of the EGFR in wing development. (A-F)
Third instar wing imaginal discs with clones that coexpress GFP (green) with either activated EGFR$^{\text{top}}$ (A-D) or Ras$^{V12}$ (E,F). (A) UAS-EGFR$^{\text{top}}$ expressing clones ectopically express aos-lacZ (A, magenta in A'), but leave N (A'') unaffected. (B) Staining for EGFR (B, B'', magenta in B') reveals its punctate accumulation in UAS-EGFR$^{\text{top}}$ clones (boxed area enlarged in B', B''). (C) In *Vps4*3B1 mutant cells marked by N accumulation (C''), EGFR$^{\text{top}}$ fails to turn on
ectopic aos-lacZ (C, magenta in C’). (D) Staining for EGFR (D, magenta in D’) confirms EGFR\textsuperscript{top} expression in Vps4\textsuperscript{3B1} mutant cells. Boxed area enlarged and DAPI channel included in D’, D”. (E) UAS-Ras\textsuperscript{V12} expressing clones ectopically express aos-lacZ (E, magenta in E’), but leave N (E”) unaffected. (F) In Vps4\textsuperscript{3B1} mutant cells marked by N accumulation (F”), Ras\textsuperscript{V12} also turns on ectopic aos-lacZ (F, magenta in F’).