Soma to neuron communication links stress adaptation to stress avoidance behavior

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Abstract

In multicellular organisms, signaling from the nervous system to the peripheral tissues can activate physiological responses to stress. Here, we show that inter-tissue stress communication can also function in reverse, i.e. from the peripheral tissue to the nervous system. *osm-8* mutants, which activate the osmotic stress response in the *C. elegans* skin, also exhibit defective osmotic avoidance behavior, which is regulated by the ASH neuronal avoidance circuit. *osm-8* osmotic avoidance behavior is completely suppressed by mutation of the Patched/NPC1 homolog *ptr-23*. The function of *osm-8* and *ptr-23* in the hypodermal epithelial cells is both necessary and sufficient for directing neuronal osmotic avoidance behavior. Endogenously tagged alleles of *osm-8* and *ptr-23* co-localize exclusively in the hypodermal lysosomes. Unbiased lipidomic analysis shows that *osm-8* leads to a *ptr-23*-dependent elevation of the lysosome specific lipid bis(monoacylglycero)phosphate (BMP) and expansion of the pool of hypodermal lysosomes. Just as genetic activation of the osmotic stress response by loss of *osm-8* in the hypodermis causes an Osm phenotype, acute physiological exposure to osmotic stress also confers a reversible Osm phenotype. Behavioral plasticity requires glycerol production, as mutations in the glycerol biosynthetic enzymes *gpdh-1* and *gpdh-2* are defective in acquired Osm behavior. While the *osm-8* induced Osm behavior requires *ptr-23*, physiologically induced Osm behavior does not. Instead, both genetic and physiologically induced Osm phenotypes require the unusual non-neuronal lysosomal V-ATPase subunit *vha-5*, which is also critical for organismal osmotic stress survival. Together, these data reveal that genetic or physiological activation of stress signaling from the skin elicits lysosome-associated signals that modulate the function of a sensory neuron circuit. Such ‘body-brain’ interoceptive communication may allow organisms to better match neuronal decision-making with organismal physiological state.

Introduction

Sensory neuron control of somatic stress responses. Cellular responses to alterations in homeostasis, such as changes in temperature, oxygen, and osmolarity, are commonly referred to as cellular stress responses. This is because cells contain autonomous mechanisms for sensing, signaling, and adapting to the particular challenges posed by each individual stressor. However, in an organismal setting, these autonomous cellular stress response pathways become subservient to systemic control mechanisms. For example, in mice, genetic or pharmacological activation of autophagy in the hypothalamic POMC neurons leads to activation of autophagy in peripheral tissues such as the liver and adipose cells (MARTINEZ-LOPEZ *et al.* 2016). In *C. elegans*, genetic activation of the mitochondrial or endoplasmic reticulum stress response in neurons leads to activation of these same stress response pathways in peripheral intestinal cells (TAYLOR AND DILLIN 2013; BERENDZEN *et al.* 2016). Similarly, optogenetic activation of temperature-sensing neurons can activate the heat shock transcription factor in the germline (TATUM *et al.* 2015). While this neuron-to-soma control of stress response pathways is now well established, what is not clear is whether or not information flows in the reverse direction, i.e. from soma to neurons. Two studies suggest that stress signaling from epithelial cells in *C. elegans* can signal to neurons to modify physiological states, such as longevity and sleep (SINNER *et al.* 2021; SAVINI *et al.* 2022). Additionally, a recent study in mice demonstrates signaling from immune cells to the brain can regulate inflammatory state (JIN *et al.* 2024). Whether or not somatic stress signaling can also modify behavioral responses to stress is not known.

Osmotic behavior and physiology in *C. elegans*. The nematode *C. elegans* exhibits two robust responses to increased environmental osmolarity, i.e. hypertonic stress. First, *C. elegans* exhibit behavioral avoidance to hypertonicity (CULOTTI AND RUSSELL 1978).

This response is driven by a well-described neuronal avoidance circuit made up of the amphid and phasmid sensory neurons ASH and PHB which signal to the command interneuron AVA to initiate backwards motion and reorientation away from the stressor (KAPLAN AND HORVITZ 1993; GAT *et al.* 2023). Second, when worms are unable to avoid hypertonicity, they activate physiological adaptation pathways, primarily in the hypodermis (LAMITINA *et al.* 2004). This includes transcriptional up- and down-regulation of >300 osmotic response genes, such as the glycerol biosynthetic enzyme *gpdh-1* (ROHLFING *et al.* 2010) via the activity of hypodermal molecular pathways controlled by the O-GlcNAc transferase *ogt-1* and the mRNA polyadenylation cleavage complex (URSO *et al.* 2020; URSO *et al.* 2023). Glycerol accumulation closely tracks extracellular solute levels which allows *C. elegans* to maintain cell and tissue volume without raising cytoplasmic ionic strength (LAMITINA *et al.* 2004). Currently, the connection between osmotic avoidance behavior and peripheral tissue osmotic stress responses are not clear. ASH osmo-sensing does not appear to be required for hypertonicity induced *gpdh-1* upregulation or glycerol accumulation in the somatic tissues (LEE *et al.* 2016). Whether or not somatic stress signaling modifies ASH osmotic avoidance behavior has not been investigated.

***osm-8* and *ptr-23*.** Upregulation of the glycerol biosynthetic enzyme *gpdh*-1 in the epithelial tissues is a robust and specific marker of the physiological response to hypertonic stress in *C. elegans* (LAMITINA *et al.* 2006). *gpdh-1* upregulation by hypertonicity is positively regulated by the O-GlcNAc transferase *ogt-1* and the polyadenylation and cleavage factor complex subunits such as Symplekin/*symk-1* (URSO *et al.* 2020; URSO *et al.* 2023). Unexpectedly, *gpdh-1* is also under extensive negative regulation, as inhibition of >100 genes cause significant upregulation of *gpdh-1* under non-stressful isotonic conditions (LAMITINA *et al.* 2006). These negative regulators result

in a physiological state change, as mutant animals become completely resistant to dehydration when exposed to extreme hypertonicity (>500mM NaCl) and accumulate the osmolyte glycerol at close to molar levels (SOLOMON *et al.* 2004; WHEELER AND THOMAS 2006). One of these negative regulators is *osm-8*, a 331 residue protein with a signal sequence and S/T-rich repeats (ROHLFING *et al.* 2011). Loss of *osm-8* leads to upregulation of *gpdh-1*, as well as most of the ORG transcription program, and accumulation of glycerol. As a result, >90% of *osm-8* mutants retain mobility in >500mM NaCl, a condition in which 0% of wild type animals are motile. Through a genetic suppressor screen, we found that all of these physiological phenotypes require the Nieman-Pick C1 (NPC1)/patched-related (ptr) receptor *ptr-23* (ROHLFING et al. 2011). Tissue-specific and temporal rescue experiments reveal that *osm-8* is required in the hypodermal epithelial cells during the L4 stage for these phenotypes. If and how *osm-8* and *ptr-23* regulate neuronal osmotic avoidance behavior has not been determined.

Here, we show that, in addition to its role in regulating peripheral physiology, *osm-8* also regulates neuronal osmotic avoidance behavior. These *osm-8* behavioral defects are completely dependent on *ptr-23*. Furthermore, the expression of *osm-8* and *ptr-23* in the hypodermis is necessary and sufficient to regulate neuronal behavior. Endogenously tagged alleles show that OSM-8 and PTR-23 co-localize to the hypodermal lysosomes. Unbiased lipidomic analysis shows that the lysosome-specific lipid bis(monoacylglycero)phosphate (BMP) exhibits *ptr-23*-dependent upregulation in *osm-8* mutants, which results in an expansion of the pool of lysosomes in the hypodermis. Acute adaptation of wild type worms to mild hypertonicity also induces a reversible osmotic avoidance defective phenotype like *osm-8*. The acquired Osm phenotype is dependent on both glycerol biosynthesis enzymes *gpdh-1* and *gpdh-2* and the lysosomal V-ATPase subunit *vha-5*, which is also required for *osm-8* behavioral

phenotypes. Together, these data suggest that the *osm-8-ptr-23-vha-5* pathway that regulates peripheral stress physiology in the skin also modulates ASH-driven behavioral sensitivity to osmotic stress, thus synchronizing behavioral and physiological states at the organismal level.

Results

***osm-8* and *ptr-23* regulate osmotic stress resistance and osmotic behavioral avoidance.** The single *osm-8* allele, *n1518*, was previously shown to constitutively upregulate the glycerol biosynthesis gene *gpdh-1*, contain elevated glycerol levels, and exhibit an osmotic stress resistance (Osr) phenotype to 500 mM NaCl, a normally lethal hypertonic stress to naïve wild type animals (ROHLFING *et al.* 2011). All of these phenotypes are dependent on the function of the patched-related receptor *ptr-23*. To create definitive null alleles for these genes, we generated deletion alleles for both *osm-8* and *ptr-23* using CRISPR/Cas9 (Fig. 1A). Similar to the originally reported alleles, the *osm-8(dr170)* allele was also Osr while the *ptr-23(dr180)* allele exhibited no Osr phenotype on its own but fully suppressed the Osr phenotype of *osm-8(d170)* (Fig. 1B). Mutations in neuron-expressed Osm genes, such as *osm-6*, do not exhibit an Osr phenotype (Fig. 1B). These new alleles represent definitive null alleles for both *osm-8* and *ptr-23* that phenocopy previously described mutants and were used for all subsequent studies, unless otherwise indicated.

While *osm-8* is annotated to exhibit Osmotic Avoidance (Osm) behavioral defects (www.wormbase.org), these phenotypes have never been described or published. When *C. elegans* encounter hypertonic environments, they first attempt to avoid the stimuli through a well characterized behavioral avoidance response (CULOTTI AND RUSSELL 1978; BARGMANN *et al.* 1990; KAPLAN AND HORVITZ 1993; TROEMEL *et al.* 1995). This avoidance response circuit is primarily driven through detection of osmotic stress via the polymodal sensory neuron ASH. In addition to hypertonicity, ASH also directs avoidance of the volatile odorant 1-octanol via mechanisms that are distinct from those involved in osmosensing (HART *et al.* 1999). *osm-8* mutants exhibited a strong Osm phenotype similar to that of other Osm mutants, such as *osm-6* (Fig. 1C). Like the Osr phenotype,

the Osm phenotype of *osm-8*, was also suppressed by *ptr-23(dr180)* or *ptr-23(RNAi)* (Fig. 1C,D). *ptr-23(RNAi)* did not suppress the *osm-6* Osm phenotype (Fig. 1D), showing that *ptr-23* is a specific suppressor of *osm-8* physiological and behavioral phenotypes.

Many Osm mutants inhibit sensory cilia formation in chemosensory neurons, which leads to characteristic morphological, functional, and behavioral phenotypes. To test if *osm-8* also alters sensory cilia formation, we first investigated the morphology or function of the ASH osmosensory neuron. Unlike *osm-6*, *osm-8* ASH neurons were able to endocytose the extracellular dye DiI, indicating the presence of functional cilia in *osm-8* (Fig. 2A). Next, we determined if the ASH neuron was generally dysfunctional or specifically dysfunctional towards hypertonicity by examining behavioral responses to 1-octanol. *osm-8* mutants exhibit a significantly shorter response latency compared to *osm-6,* indicating that this behavioral modality is not strongly affected in *osm-8* (Fig. 2B). Finally, we compared the behaviors of *osm-6* and *osm-8* in the Osm ring assay (CULOTTI AND RUSSELL 1978). *osm-6* exhibits relatively few ring encounters because they tend to cross the ring very early in the assay (Fig. 2C,D). In contrast, *osm-8* mutants have many more ring encounters and do not cross the ring until much later in the assay as compared to *osm-6* (Fig. 2C,D). Together, these data show that *osm-8* is required for osmotic avoidance behavior and that this phenotype is not due to defects in ASH neuron development or gross abnormalities in the ASH avoidance circuit. However, the kinetics of avoidance in *osm-8* was significantly delayed compared to *osm-6*, suggesting they regulate avoidance through different mechanisms.

There are at least two classes of Osm mutants. Class 1 mutants, such as *osm-6*, are required for the formation of sensory cilia, while Class 2 mutants, such as the TRPV channel *osm-9* (COLBERT *et al.* 1997), have normal cilia but are nonetheless functionally defective in the ability to detect all ASH stimuli. Both Class 1 and Class 2 genes are

expressed in ASH, as well as other ciliated sensory neurons. When we examined the single cell gene expression map for the *C. elegans* nervous system (TAYLOR *et al.* 2021), we found that the expression of both Class 1 and Class 2 Osm genes were dramatically enriched in neurons and absent from the hypodermal cells (Fig. 3A). Consistent with previous studies using overexpression reporter transgenes (ROHLFING *et al.* 2011), expression of both *osm-8* and *ptr-23* mRNA exhibit the inverse pattern - they were not detected in sensory neurons, including ASH, but were highly enriched in the hypodermis (Fig. 3A). These expression data suggest the possibility that *osm-8* and *ptr-23* may alter neuronal osmosensing via their function outside of the nervous system.

Hypodermal function of *osm-8* and *ptr-23* is necessary and sufficient for both physiological stress resistance and neuronal stress avoidance behavior. To test if *osm-8* and *ptr-23* act outside of the nervous system to control behavior, we took two approaches. First, we utilized tissue-specific rescue constructs to restore *osm-8* or *ptr-23* expression solely in the hypodermis and examined their ability to rescue *osm-8* or *osm-8;ptr-23* Osm phenotypes. In *osm-8* mutants, rescue of *osm-8* using either its endogenous promoter or the hypodermal cell specific *dpy-7* promoter fully rescued both the Osr and Osm phenotypes (Fig. 3B,C). Likewise, in *osm-8;ptr-23* mutants, expression of *ptr-23* from either its endogenous promoter or the hypodermal cell specific *dpy-7* promoter restored the Osr and Osm phenotypes (Fig. 3B,C). Therefore, expression of both *ptr-23* and *osm-8* in the hypodermis is sufficient for rescue of neuronal behavioral defects.

Second, we utilized tissue specific RNAi strains in which genes could be inhibited in either the hypodermis or the intestine (WATTS *et al.* 2020). Since *osm-8* does not produce a strong or consistent RNAi phenotype (ROHLFING *et al.* 2011), we engineered the *osm-8* deletion into each of these strains using CRISPR/Cas9 and performed *ptr-*

23(RNAi). In a global RNAi background, *ptr-23(RNAi)* fully suppressed the Osm and Osr phenotypes of *osm-8* (Fig. 3D,E). Likewise, when RNAi was restricted to the hypodermis, *ptr-23(RNAi)* also fully suppressed the Osm and Osr phenotypes of the *osm-8* mutant (Fig. 3D,E). However, in an intestine-restricted RNAi strain, *ptr-23(RNAi)* had no effect of any *osm-8* phenotypes (Fig. 3D,E). Taken together, the rescue and tissue specific RNAi data show that *osm-8* and *ptr-23* expression outside of the nervous system in the hypodermis is necessary and sufficient to regulate the physiological Osr and the behavioral Osm phenotypes.

OSM-8 and PTR-23 are co-localized to hypodermal lysosomes and regulate lysosome abundance and volume. We previously generated a rescuing *osm-8::GFP* transgene and failed to observe any fluorescent signal (ROHLFING *et al.* 2011). Since *osm-8* contains a canonical N-terminal signal sequence, this led us to speculate that OSM-8::GFP might be secreted into a cellular compartment that is recalcitrant to GFP folding and/or fluorescence (EVANS *et al.* 2023). To better understand how *osm-8* and *ptr-23* might be regulating behavioral and physiological phenotypes, we generated endogenously tagged alleles using environmentally stable, monomeric fluorophores. Both *osm-8:mNeonGreen* and *ptr-23:mScarlett* alleles were functional, since *osm-8::mNG* did not exhibit an Osr phenotype and *ptr-23:mSc* did not suppress the *osm-8(dr170)* Osr phenotype. We observed that both OSM-8::mNG and PTR-23::mSc were only expressed in the hypodermis where they exhibited strong co-localization during the L4 stage of development (Fig. 4A-C). However, in adults, OSM-8 was no longer detectable, while PTR-23 was still present (Fig. 4D-F). During the L4 stage, PTR-23::mSc co-localized with the lysosomal marker SCAV-3::sfGFP while OSM-8::mNG co-localized with the lysosomal marker NUC-1::mCh. An OSM-8:sfGFP allele, which is only visible in non-acidic compartments, showed brief localization to cuticular furrows during

the L4 stage but was similarly undetectable in adult animals (Fig. 4N,O), suggesting OSM-8 may be a pre-cuticular protein that is endocytosed and degraded in the lysosome. However, PTR-23::mSc was only observed in the lysosomes, suggesting that *osm-8*-dependent signaling occurs through *ptr-23* function in the lysosome.

Given the association of OSM-8 and PTR-23 with the lysosome, which is a major regulator of lipid metabolism, and the established roles of Patched and Patched-related genes in the transport of hydrophobic molecules including lipids, we hypothesized that *osm-8* and *ptr-23* may regulate lipid homeostasis. Therefore, we performed unbiased liquid chromatography-high resolution mass spectrometry (LC-HRMS) to identify *osm-8* induced, *ptr-23*-dependent changes in relative lipid abundance. We identified 2,708 distinct lipid species among all 3 genotypes (wild type, *osm-8(dr170)*, *osm-8(dr170); ptr-23(dr180)*). Notably, we found that the lysosome/endosome-specific lipid bis(monoacylglycero)phosphate (also known BMP) was upregulated in *osm-8* mutants but restored to wild type levels in *osm-8; ptr-23* mutants (Fig. 5A,B,C,D). osm-8 upregulated primarily polyunsaturated BMP species, while monounsaturated species were unaffected (Fig. 5C), indicating some level of specificity in the upregulation of BMP lipids by *osm-8*. Interestingly, the proposed precursor for BMP synthesis, phosphatidylglycerol (PG) (CHEN *et al.* 2023; MEDOH *et al.* 2023; BULFON *et al.* 2024; SINGH *et al.* 2024), did not increase in *osm-8* but was reduced in *osm-8; ptr-23* (Fig. 5E). Triglycerides, which would be predicted to be elevated in *osm-8* mutants due to the extreme levels of glycerol accumulation, were actually reduced in *osm-8* and this was partially reversed in *osm-8; ptr-23* (Fig. 5F). Similar to previous studies, elevation of BMP by *osm-8* also led to increased cholesterol storage, which is known to mainly occur in the lysosome (MCCAULIFF *et al.* 2019). Cholesterol levels were partially reversed in

osm-8; ptr-23 animals (Fig. 5G). Together, *osm-8* and *ptr-23* play key roles in the homeostasis of the lysosomal lipid BMP and accumulation of cholesterol.

The elevation in BMP lipids observed in *osm-8* suggests that lysosome homeostasis may also be altered in *osm-8*. To test this, we examined lysosomal abundance in the hypodermis of *osm-8*, *ptr-23*, and *osm-8; ptr-23* mutants using the lysosomal marker *nuc-1:mCherry*. We observed a significant increase in the number of hypodermal lysosomes in *osm-8* (Fig. 6A). Automated image analysis revealed that the increase in hypodermal lysosomes seen in *osm-8* was completely eliminated in *osm-8; ptr-23* animals (Fig. 6B). *ptr-23* alone had no effect on the size of the lysosome pool. The increase in the number of lysosomes did not seem to be due to increased autophagy as the abundance of the autophagosomal marker *lgg-1:gfp:mCherry* was not altered by *osm-8* (Fig. 6C). We conclude that *osm-8* and *ptr-23* regulate lysosomal abundance through an autophagy-independent mechanism.

Acute physiological adaptation of wild type animals to mild hypertonic stress induces a reversible Osm phenotype that requires glycerol biosynthesis and the lysosomal ATPase subunit *vha-5*. *osm-8* mutants genetically activate the same gene expression program seen in wild type animals exposed to non-lethal adaptive levels of hypertonicity (ROHLFING *et al.* 2010) and the expression of many, but not all, of these genes depends on *ptr-23* (ROHLFING *et al.* 2011). We hypothesized that the osmotic avoidance behavioral phenotypes observed in *osm-8* might be replicated in wild type animals by acutely exposing them to mild hypertonic stress. To test this prediction, we exposed wild type animals to 250 mM NaCl for 1, 3, 6, or 24 hours and then performed Osm behavioral ring assays. While non-adapted animals are not Osm, we observed that wild type animals started exhibiting Osm behavior after only 3 hours of adaptation and this increased by 24 hours (Fig. 7A). The acquired Osm behavior in wild type animals

was reversed by shifting animals back to 50 mM NaCl and was back to baseline levels after 6 hours (Fig. 7A). These data show that the Osm behavior is a physiologically acquired and reversible phenotypic trait that is constitutively activated in *osm-8* mutants.

One major physiological consequence of osmotic adaptation in *C. elegans* is accumulation of the organic osmolyte glycerol (LAMITINA *et al.* 2004). Genetic deletion of the glycerol-3-phosphate dehydrogenase enzymes *gpdh-1* and *gpdh-2* reduces the accumulation of glycerol by ~50% (LAMITINA *et al.* 2006). To test if glycerol is required for adaptation induced Osm behavior, we adapted *gpdh-1*, *gpdh-2*, and *gpdh-1; gpdh-2* knockouts and analyzed their Osm behavior. We found that Osm behavior was significantly reduced in the *gpdh-1; gpdh-2* double mutants (Figure 7B). This suggests that adaptation induced Osm behavior requires production of glycerol.

We hypothesized that adaptation induced Osm behavior may require *ptr-23*, since it is required for *osm-8*-induced Osm behavior. However, acquired Osm behavior was not affected by loss of *ptr-23* (Fig. 7C). Therefore, we re-examined our prior list of *osm-8* suppressors (ROHLFING *et al.* 2011) and tested if any were required for adaptation induced Osm behavior. We found that the lysosomal ATPase subunit *vha-5* was required for both *osm-8* and wild type acquired Osm behavior (Fig. 7D). *vha-5* is only expressed in the hypodermis and excretory cell suggesting that, like *ptr-23*, *vha-5* regulates Osm neuronal behavior from outside the nervous system (OKA *et al.* 2001; LIEGEOIS *et al.* 2006; LIEGEOIS *et al.* 2007). We next tested whether *vha-5* and *ptr-23* were required for overall physiological survival in response to osmotic stress. Exposure of wild type animals to 250mM NaCl is sufficient to activate the osmotic stress response but is not lethal after 24 hours. While loss of *ptr-23* did not reduce survival, *vha-5(RNAi)* led to a significant reduction in survival, which was also observed in the *ptr-23* mutant (Fig. 7E). Together, we conclude that *osm-8* and *ptr-23* comprise one branch of a

multipronged osmotic stress response pathway, which converges on the regulation of the lysosomal ATPase subunit *vha-5* and that signaling from the hypodermal lysosome is required to suppress neuronal osmotic avoidance behavior and promote organismal survival (Fig. 7F).

Discussion

Peripheral stress resistance pathways drive changes in behavior. Our data show that a behavioral avoidance neuronal circuit can be over-ridden by the activation of stress response pathways in peripheral cells. Genetic or physiological activation of osmotic stress response pathways in the barrier hypodermal cells was sufficient to overcome the high-fidelity sensitivity of the ASH avoidance circuit. This effect was specific for the osmotic avoidance modality of the ASH circuit, since octanol response latency was unaffected. Interestingly, the time course of physiological adaptation and reversal closely matches the accumulation kinetics of the organic osmolyte glycerol and the glycerol biosynthetic enzymes *gpdh-1* and *gpdh-2* were required for physiological adaptation. This suggests an elegant feedback model in which the activation of a physiological response in the peripheral skin tissues produces a metabolite(s) that both blunts the ability of a sensory neuron to detect and avoid threatening environments and enhances organismal survival. Such interoceptive 'body-brain' axis signaling between the peripheral digestive system and the brain for the regulation of feeding behavior is well documented (STOVER *et al.* 2023). However, our studies of the osmotic stress response and *osm-8* signaling show that such interoceptive signaling is more pervasive than previously appreciated and also takes place outside of the gustatory system.

***osm-8-ptr-23* regulation of lysosomes may play a key role in communicating physiological state to the nervous system.** We showed that *osm-8* and *ptr-23* play essential roles in coordinating stress physiology with behavior. Surprisingly, we find that both genes carry out these functions from the hypodermis. In the case of OSM-8, we find that its accumulation during the L4 stage and disappearance in the adult precisely matches the temporal rescue requirements that we previously defined (ROHLFING *et al.* 2011). While OSM-8 and PTR-23 are localized to lysosomes, regulate lysosome

abundance, and control the abundance of lysosome-specific lipids such as BMP, the role of the lysosome in osmotic physiology remains enigmatic. A previous genome wide RNAi screen identified several lysosomal genes as being required for hyperosmotic survival, although *vha-5* was not among the genes identified (CHOE AND STRANGE 2008). Another recent study shows that mutation of the cuticular collagen *dpy-7*, which causes an Osr phenotype similar to *osm-8*, exhibits upregulation of some lysosomal genes (FONG *et al.* 2024). One possibility is that lysosomes generate signaling molecules which lead to activation of the osmotic stress response and production of secretory factors that attenuate osmotic avoidance behavior. Such a paradigm was recently described for the role of intestinal lysosomes during aging (SAVINI *et al.* 2022). Another possibility is that the increase in lysosomal abundance and BMP lipids is a downstream consequence of the activation of glycerol accumulation by *ptr-23*-dependent signaling upon loss of *osm-8*. BMP is the major phospholipid constituent of intralumenal membranes of the late endosome/lysosome, where it regulates sorting and degradation of lipids or lipid cargo (KOBAYASHI *et al.* 1998). BMP is composed of two monoacylglycerols linked by a phosphate. Elevation of glycerol could drive increased flux through the BMP biosynthesis pathway, resulting in the expansion of BMP enriched lysosomal membranes. The synthesis mechanism of BMP is not well understood, although several enzymes were recently suggested to catalyze different steps in its biosynthesis (CHEN *et al.* 2023; MEDOH *et al.* 2023; BULFON *et al.* 2024; SINGH *et al.* 2024). Whether or not these genes play important roles in the generation of BMP by the *osm-8/ptr-23* pathway or contribute to the osmotic stress response will require further study.

The V-ATPase proton pump plays a key role in lysosomal physiology by generating the acidic environment required for many aspects of lysosomal function. Like *ptr-23*, the V-ATPase subunit *vha-5*, but none of the other *vha* genes, is required for the *osm-8*

phenotypes. This suggests that the lysosomal functions of *osm-8*, *ptr-23,* and *vha-5* may not be pH-dependent. *vha-5* has well established V-ATPase-independent roles in *C. elegans*, including in the secretion of proteins from the hypodermis as well as serving as a marker of specialized apical plasma membrane structures called meisosomes (LIEGEOIS *et al.* 2006; AGGAD *et al.* 2023). Whether or not the meisosomal functions of *vha-5* are required cannot yet be determined since mutations that specifically affect this function(s) are not known.

ptr-23 is part of the expanded Patched Receptor (*ptc*) and Patched-related (*ptr*) gene family which includes >20 genes in *C. elegans* (ZHONG *et al.* 2014). *ptr* genes have established roles in molting and apical extracellular matrix development, as well as the formation of unicellular tube structures (COHEN *et al.* 2021). While Patched and Patched-related proteins are thought to be hydrophobic transporters due to their overall similarity with bacterial resistance-nodulation division (RND) transporters, their specific transport substrates are mostly unknown. One exception is the Patched homolog NPC1, which encodes a lysosomal cholesterol transporter associated with inherited metabolic disorder Niemann-Pick Disease (SAHA *et al.* 2020). Mutations in NPC1 cause lysosomal accumulation of cholesterol and elevation of the lipid BMP (MCCAULIFF *et al.* 2019). This causes NPC1 patients to develop a progressive form of ataxia in adolescence and adulthood. Interestingly, we find that mutations in *osm-8* mimic the lipid phenotypes of NPC1 mutations by raising BMP and cholesterol levels. Conversely, we find that mutation of the NPC1-related gene *ptr-23* reverses the *osm-8* induced changes in lipid composition by lowering cholesterol and BMP. Thus, even though PTR-23 localizes to the lysosome and has sequence similarity to the NPC1 gene, it is unlikely to function as a cholesterol transporter. Consistent with this, many of the key residues required for cholesterol transport in NPC1 are not conserved in PTR-23 (SAHA *et al.* 2020). Further

analysis of the Osr/Osm mutant genetic pathway should help to better understand how OSM-8 and PTR-23 contribute to these dramatic lipidomic and phenotypic changes.

Physiological signals that drive changes in the nervous system from the hypodermal lysosome. The precise molecular mechanism by which hypodermal osmotic stress signaling represses the osmotic behavioral response remains unclear. Our data show that adaptation induced behavioral changes are reduced but not eliminated in animals lacking the biosynthetic enzymes *gpdh-1* and *gpdh-2*, likely due to the fact that these mutants reduce but do not eliminate accumulation of glycerol under hypertonic conditions (LAMITINA *et al.* 2006). Other mechanisms could also contribute to the observed behavioral plasticity. For example, a previous study demonstrated that lysosomes can generate lipid signals in non-neuronal somatic cells that alter nervous system function and behavior (SAVINI *et al.* 2022). Given the significant changes in lipid content in *osm-8* mutants, it is possible that such lipid signals may also be involved here. Yet another possibility is that the secretion of several hypodermal expressed neuropeptides, which are upregulated by both *osm-8* and osmotic stress (ROHLFING *et al.* 2010), may communicate with neurons to modify their responses to osmotic stimuli. These neuropeptides are similarly upregulated by infection and were previously shown to regulate infection-induced behavior (SINNER *et al.* 2021). Future studies will be aimed at testing each of these models.

Surprisingly, we found that while loss of *ptr-23* is required for the behavioral adaptation induced by loss of *osm-8*, it is not required for physiological behavioral adaptation induced by high salt. Previously, we showed that even in the absence of *ptr-23*, hypertonicity could still activate upregulation of *gpdh-1* (ROHLFING *et al.* 2011). These data suggests that there is a parallel pathway(s) that regulates the peripheral osmotic stress response and can communicate with neurons. The observation that *vha-5(RNAi)*

blocks adaptation induced behavioral changes suggests that this pathway may function in parallel to *ptr-23* and that both pathways converge on *vha-5*. Candidates for such a pathway include the related secreted proteins *osm-7* and *osm-11* (WHEELER AND THOMAS 2006; KOMATSU *et al.* 2008), which may act independently of *ptr-23* (VEROLI AND LAMITINA 2023). Unlike *osm-8*, *osm-7* and *osm-11* also alter octanol response latency (SINGH *et al.* 2011). This suggests that *osm-7* and *osm-11* might modify the ASH avoidance circuit through a different mechanism from *osm-8*. Additional studies, including physiological analysis of the activity of the ASH circuit in these mutant backgrounds, will be important to test these models.

In conclusion, our data reveals a non-gustatory 'body-brain' axis in *C. elegans* that links peripheral physiological state with behavioral plasticity. The sensation and integration of internal physiological state by the nervous system, a process called interoception, is an emerging but poorly understood process (KHALSA *et al.* 2018). By activating a physiological stress response pathway without altering external environmental input, the *osm-8-ptr-23* pathway in *C. elegans* represents a primitive but tractable interoceptive state in which to define the interoceptive signals that arise from the peripheral tissue, the interoreceptors on neurons, and the mechanisms by which these signals modulate the nervous system. Such mechanisms could provide insights into a wide variety of conditions associated with disruptions in the body-brain axis, such as depression (AVERY *et al.* 2014), autism (HATFIELD *et al.* 2019), post-traumatic stress syndrome (SIMMONS *et al.* 2009), and chronic pain (SUAREZ-ROCA *et al.* 2019).

Materials and methods

***C. elegans* strains and culture**: All strains were cultured at 20ºC. A table of all strains used in these studies can be found in Table 1. Wormbase was utilized as the source for all genomic sequence data (STERNBERG *et al.* 2024).

Osmotic stress resistance, adaptation, and osmotic avoidance assays: All assays were performed with Day 1 adults (24 hours post L4 stage). For Osr assays, four replicates of 20 animals were placed in a glass depression slide containing 200µl of M9 with 550 mM NaCl. The number of animals exhibiting movement after 10 minutes was counted.

Osm behavioral assay were performed as previously described (CULOTTI AND RUSSELL 1978), with slight modifications. We printed a ring of 4M NaCl, 0.1% light green SF yellowish dye, pH 7.0 onto standard 3cm NGM plates using a 12mm Falcon snap cap as a template. The cap was gently placed on the agar surface and 40µl of 4M NaCl solution was evenly pipeted around the edge of the cap. The cap was then removed and the 4M NaCl solution was allowed to soak into the plate for 5 minutes prior to the start of the assay. For each assay, 10 day 1 adult animals were placed in S-buffer for ~1 minute to remove bacteria and then placed in the center of the ring using an eyelash pick. Eight replicates of 10 animals were performed for each genotype and/or condition. After 30 minutes, each plate was scored for the number of animals that crossed the ring. Animals that paralyzed on the ring were censored. To prevent animals from re-entering the ring after crossing, we placed a 10ul spot of OP50 or *empty vector(RNAi)* HT115 bacteria on the outer edge of the plate to which worms navigated and dwelled once they crossed the ring. The presence of food did not result in wild type animals crossing the ring, even after up to 1 hour.

For the analysis of ring encounters and ring dwell time, we collected video (2 frames per second) of the whole 3cm plate over the course of the 30 minute Osm assay using the Wormlab imaging system (N=5-6 animals per video, 4-6 videos per genotype, 18-21 animals total per genotype. Animals were picked into 5µl of S-buffer in the center of the ring to prevent engagement with the ring prior to starting the video recording. After each plate was recorded, worms were tracked using WormLab software throughout the course of the 30 minutes. In order to differentiate an encounter from a crossing, two concentric circular labels were created in WormLab, where one label denoted the inner boundary of the ring and the other label denoted the outer boundary. The sizes of these labels were saved and applied to each video. A worm crossing the first label was denoted as an 'encounter', and the same worm crossing the second label was denoted as an escape. The number of encounters a worm underwent was counted, and the time before which the worm escaped the outer label was recorded in seconds. Once a worm crossed the ring, it was no longer considered throughout the remainder of the video. If a worm did not cross the ring after 30 minutes, the time in the ring was denoted as 1800 seconds. Animals that paralyzed inside or on the ring were censored from the analysis.

Octanol response assay - The 1-octanol avoidance assays were performed as previously published with some modifications (TROEMEL *et al.* 1995). The morning before conducting the assay, 4µl of OP50 were seeded as 10 separate spots on five 60mm NGM plates per strain and allowed to dry for ~30 minutes at room temperature. Ten day 1 animals were placed individually onto each spot and left to acclimate to the new plate conditions for approximately 30 minutes. During that time, 1-octanol was diluted to 10% in 100% ethanol. 50µl of diluted 1-octanol was aliquoted into separate PCR tubes for the assays. The 1-octanol aliquots were kept sealed and twelve feet away from the

nematodes when assessing 1-octanol avoidance. For the experiments, a fresh horsehair was parafilmed onto the tip of a Q-tip. Then the horsehair was saturated in the diluted 1-octanol, avoiding the parafilm. Then, the horsehair was placed in front of the forward-moving animal. The 1-octanol avoidance response time was recorded upon initiation of backward locomotion. For the subsequent two biological replicates per animal, the horsehair was re-saturated in diluted 1-octanol following the recording of avoidance time to ensure the presence of the odorant throughout the assay.

Osmotic Survival Assays - Day 1 adults placed onto *empty vector(RNAi)* or *vha-5(RNAi)* plates and incubated for ~65-72 hr at 20°C. Progeny L4 stage animals were then placed onto either the control or high salt RNAi plates containing 250mM NaCl. 24 hours later, day 1 adults were tested for survival by tapping the plate and by tapping the worm's body. Animals that moved forward or backward one full body length were scored as alive.

Imaging and microscopy: L4 stage or day 1 adult animals were immobilized in 50mM levamisole. For images in Figure 4, widefield *nuc-1:mCherry* images were collected as a Z-series (0.27µm step size) on a Leica DMI4000 equipped using a 63x/1.4N.A. lens and a DFC365 digital camera. For quantification of lysosome number, three non-overlapping 25.69µm x 25.69µm x 8.64µm sections centered on the *nuc-1:mCherry* signal in the hypodermis were cropped from each master image. Each cropped section was deconvolved using identical standard settings in imaging software (Leica AF). Puncta in the 3D deconvolved cropped Z-stacks were then analyzed using Aivia software. Training took place on one wildtype image stack and equivalent threshold settings were then applied to all image stacks for all genotypes to generate object counts.

Transgene rescue experiments: *osm-8* and *ptr-23* genomic fragments containing the promoter (~2Kb), coding sequence, and 3' UTR (~1Kb) was PCR amplified (Q5 polymerase, New England Biolabs) and cloned into the pMinT2.0 vector. To derive clones with hypodermal-specific expression, we replaced the *osm-8* or *ptr-23* promoters with a *dpy-7* promoter using recombination-based cloning (High-fidelity assembly, NEB). The sequence of all plasmids was verified by whole-plasmid DNA sequencing (Plasmidsaurus).

To generate *osm-8* rescue lines, we microinjected *osm-8(dr170)* with a mix containing pBluescript II (80ng/µl), pCFJ90/*myo-2p::mCherry* (2ng/µl), and the *osm-8* rescue plasmid (20ng/µl or 2ng/µl for the *dpy-7p* plasmid, which was toxic at higher concentrations). To generate *ptr-23* rescue lines, we injected *osm-8(dr170); ptr-23(dr180)* with a mix containing pBluescript II (80ng/µl), pCFJ90/*myo-2p::mCherry* (2ng/µl), and the *ptr-23* rescue plasmid (20ng/µl or 2ng/µl for the *dpy-7*p plasmid, which was toxic at higher concentrations). Stable extrachromosomal array lines that segregated *myo-2p::mCherry* in the progeny were selected for analysis.

CRISPR/Cas9 genomic editing: The *osm-8* deletion allele *dr170* and the *ptr-23* deletion allele *dr180* were generated using previously described CRISPR/Cas9 editing methods (VEROLI AND LAMITINA 2023). mNeonGreen and mScarlett tags were amplified from pJW2171 and pJW2098 (ASHLEY *et al.* 2021) and inserted into the endogenous *osm-8* or *ptr-23* genes using our standard CRISPR/Cas9 methods (URSO *et al.* 2023). Both tagged alleles were functional as determined by their lack of an Osr phenotype (*osm-8(dr170*)) or their inability to suppress the *osm-8* Osr phenotype (*ptr-23(dr180))*. All

alleles were verified by DNA sequencing. A table of all primers used in this study can be found in Table 2.

Lipidomics – For each replicate, N2, *osm-8(dr170)*, and *osm-8(dr170); ptr-23(dr180)* animals were seeded on 3x15 cm NGM plate with a lawn of OP50 as starved L1s. Animals were grown at 20ºC until animals were day 1 adults. We collected a total of six replicates for each genotype for analysis. Worms were washed off plates using M9 buffer, pelleted in a swinging bucket centrifuge at 2,000xg for 1 minute, and then washed three times. Worm pellets were resuspended in 10ml of M9 buffer and incubated at 20ºC with rocking for 15 minutes to evacuate OP50 bacteria from the intestine. Worms were pelleted and the density of worms per microliter was calculated for each strain. For each sample, ~5,000 worms were pipeted into 2.0ml tubes containing a MP Bio Matrix A (garnet/ceramic sphere) and frozen at -80ºC prior to processing.

Metabolic quenching, lysis, and lipid extraction was performed by adding 0.5mL ice cold phosphate buffered saline. Samples were homogenized in MP Biomatrix A tubes at 60 Hz for 1 minute. Uncleared supernatant (400 µL) was transferred to a clean glass tube containing 10 µL of LipidSplash, deuterated internal standards (Avanti Polar Lipids. Alabaster, AL) and subjected to Folch extraction. Samples were rested on ice for 10 minutes before phase separation via centrifugation at 2500 x g for 15 minutes. The organic phase (0.7 mL) was transferred to a clean glass vial and dried to completion under N2. Samples were resuspended in 100 µL of 1:1 acetonitrile:isopropanol and 3µL was injected for online LC-HRMS analysis.

Briefly, samples were injected via a Thermo Vanquish UHPLC and separated over a reversed phase Thermo Accucore C-18 column (2.1×100mm, 5µm particle size) maintained at 55°C. For the 30 minute LC gradient, the mobile phase consisted of the

following: solvent A (50:50 H2O:ACN 10 mM ammonium acetate/0.1% acetic acid) and solvent B (90:10 IPA:ACN 10 mM ammonium acetate/0.1% acetic acid). The gradient started at 30% B and increased to 43%B over 2 minutes followed by an increase to 55%B in 0.1 minute. The organic increased to 65%B over the next 10 minutes, followed by an increase to 85%B over 6 minutes. For column washing the gradient increased to 100%B over 2 minutes and was held for 5 minutes followed by 5 minutes of equilibration at 30%B. The Thermo ID-X tribrid mass spectrometer was operated in both positive and negative ESI mode. A data-dependent MS2 method was used with scanning in Full MS mode from 200 to 1500 m/z at 120,000 resolution with an AGC target of 5e4 for triggering MS2 fragmentation using stepped HCD collision energies at 20, 40, and 60% in the Orbitrap at 15,000 resolution. Source ionization settings were 3.5kV and 2.4kV spray voltage, respectively for positive and negative mode. Source gas parameters were 35 sheath gas, 5 auxiliary gas at 300°C, and 1 sweep gas. Calibration was performed prior to analysis using the PierceTM FlexMix Ion Calibration Solutions (Thermo Fisher Scientific). Internal standard peak areas were then extracted manually using Quan Browser (Thermo Fisher Xcalibur ver. 2.7), normalized to weight and internal standard peak area, then graphed using GraphPad PRISM (ver 9.0). Untargeted differential comparisons were performed using LipidSearch 4.2 (Thermo Fisher) to generate a ranked list of significant lipid compounds at the class and species-specific levels.

Statistical Analysis: Comparisons of means were analyzed with either a two-tailed Students t-test (2 groups) or ANOVA (3 or more groups) using either the Dunnett's, Sidak, or Tukey's post-test analysis as indicated in GraphPad Prism 9 (GraphPad Software, Inc., La Jolla, CA). p-values of <0.05 were considered significant.

Data Availability Statement: Strains and plasmids are available upon request. The authors affirm that all data necessary for confirming the conclusions of the article are present within the article, figures, and tables.

Acknowledgements

This work was supported by NIH R01GM135577 to T.L. and NIHS10OD023402 to S.G.. Some mutant strains were provided by the CGC, which was funded by the NIH Office of Research Infrastructure Programs (P40 OD010440).

Conflict of Interest Statement

The authors have no conflicts of interest to declare

Table 1. Strains used in this study

Strain	Genotype	Source
N2	+/+	CGC
MT3571	*osm-8(n1518)*	CGC
OG2201	*osm-8(dr170)*	This study
PR811	*osm-6(p811)*	(CULOTTI AND RUSSELL 1978)
MAH215	*sqIs11 [lgg-1p:lgg-1::mCherry::gfp::lgg-1 3'UTR; rol-6]*	(CHANG *et al.* 2017)
OG1117	*ogt-1(jah01)*	(KONZMAN *et al.* 2022)
OG2199	*qxIs722; ptr-23(dr169) [CRISPR ptr-23 MScarlet]*	This study
OG2180	*osm-8(dr163) [CRISPR insertion of mNeonGreen at C-terminus of endogenous osm-8 genomic locus]*	This study
OG2192	*osm-8(dr165) [osm-8:mSc CRISPR]; qxIs722 [dpy-7p::dpy-7::sfGFP]*	This study
OG2200	*osm-8(dr163); qxIs257 [ced-1p:nuc-1::mCherry]*	This study
OG2210	*ptr-23(dr169) [ptr-23:mSc]; qxIs430 [scav-3::gfp]*	This study
OG2215	*ptr-23(dr179) [CRISPR ptr-23 del.]; osm-8(n1518); qxIs257*	This study
OG2216	*osm-8(n1518); qxIs257*	This study
OG2217	*ptr-23(dr180); qxIs257*	This study
OG2255	*osm-8(dr170); drEx524 [osm-8p::osm-8 genomic DNA (10ng/ul); myo-2p::mCherry (2ng/ul); pBSII (80ng/ul)]*	This study
OG2256	*osm-8(dr170); ptr-23(dr180); drEx525 [ptr-23p::ptr-23 genomic DNA (10ng/ul); myo-2p::mCherry (2ng/ul); pBSII (80ng/ul)]*	This study
OG2257	*frSi17 [mtl- 2p::rde-1 3'UTR]; frIs7 [nlp-29p::GFP + col-12p::DsRed]; rde-1(ne300); osm-8(dr187) [CRISPR osm-8 deletion into IG1839]*	This study
OG2258	*frSi21 [col-62p::rde-1 3'UTR]; frIs7 [nlp-29p::GFP + col-12p::DsRed]; rde-1(ne300); osm-8(dr188) [CRISPR osm-8 deletion into IG1846]*	This study
OG2263	*osm-8(dr170); drEx526 [dpy-7p::osm-8 genomic DNA (1ng/ul), myo-2p::RFP(2ng/ul), pBSII(100ng/ul)]*	This study
OG2264	*osm-8(dr170); ptr-23(dr180); drEx527 [exdpy-7p::ptr-23 genomic DNA(1ng/ul), myo-2p::RFP(2ng/ul), pBSII (100ng/ul)]*	This study

OG2266	*symk-1(dr88)*	(URSO *et al.* 2023)
OG2267	*osm-8(dr190) [CRISPR sfGFP]*	This study
OG2271	*ptr-23(dr180) [ptr-23 deletion]*	This study
OG2272	*ptr-23(dr180); osm-8(dr170)*	This study
OG2274	*gpdh-2(dr195)*	This study
OG2275	*gpdh-1(dr154)*	(VEROLI AND LAMITINA 2023)
OG2276	*gpdh-1(dr154); gpdh-2(dr195)*	This study
XW5399	*unc-76(e911); qxIs257 [ced-1p::nuc-1::mCherry + unc-76(+)]*	(LI *et al.* 2016)
XW8056	*unc-76(e911); qxIs430 [scav-3 GFP]*	(LI *et al.* 2016)
XW18042	*qxIs722 [dpy-7p::dpy-7::SfGFP]*	(MIAO *et al.* 2020)

Table 2. Oligos used in this study

Primer	Sequence	Purpose
OG108	TTCGTCATTTCCGAAGCTATCATCA	*osm-8* genomic rescue sense
OG109	ATCGGCGTTGGAGCAACATA	*osm-8* genomic rescue antisense
OG2174	TTCTTAGCAGGCGGAGAAGC	*osm-8* C-terminal gRNA
OG2177	GTTCACTACACCATCTCCTCCACA	*osm-8* C-terminal fluorescent reporter genotyping, sense
OG2178	gcaagaggagcagcttctcaacctc	*osm-8* C-terminal fluorescent reporter genotyping, antisense
OG2241	gtattttgcactacgggtcg	*gpdh-2* N-terminal gRNA
OG2252	GCATTTGTGCAGGTGCATCT	*osm-8* N-terminal gRNA
OG2276	tatttccaagcagaaaaagcaaaatgtttgacttcttggctggaggggaggctggacgacttcttgga ggtggcggtggatcgggaggag	*osm-8:mScarlett:AID:3XFLAG* C-terminal repair template primer, sense
OG2277	gttcacaaataatttaaagcgaaaaaaataaatTTAGCCTCCGGACGATGCTCCT GAGGCTCC	*osm-8:mScarlett:AID:3XFLAG C-terminal repair template primer, antisense*
OG2278	GAGTGTGGTCACTGATCGAC	*ptr-23* C-terminal gRNA
OG2279	gttcagccggaaaagagtgtggtcactgatcgacctgaaatcggtggcggtggatcgggaggagg	*ptr-23:mSc:AID:3XFLAG* C-terminal repair template primer, sense
OG2280	AAGTTAAAAAGAAATATAATTAATGGTTTTTTTTAGCCTCCGGACGA TGCTCCTGAGGC	*ptr-23:mSc:AID:3XFLAG* C-terminal repair template primer, antisense
OG2281	CTTCATGGTCTCGTGTTCTTACC	*ptr-23:mSc:AID:3XFLAG* genotyping primer outer sense
OG2282	cttacctgctatcttgattcttttg	*ptr-23:mSc:AID:3XFLAG* genotyping primer inner sense
OG2283	CATGGATCCGCCTCCTCCTGAAC	*ptr-23:mSc:AID:3XFLAG* genotyping primer outer antisense
OG2284	TCCTCCTGAACCACCGCCGCCAC	*ptr-23:mSc:AID:3XFLAG* genotyping primer inner antisense
OG2285	gactacaaagaccatgacggtg	*ptr-23:mSc:AID:3XFLAG* genotyping primer outer sense

OG2286	gacggtgattataaagatcatg	*ptr-23:mSc:AID:3XFLAG* genotyping primer inner sense
OG2287	GGCAAAATGAAACTCAAGAAGAT	*ptr-23* deletion screening primer, outer antisense
OG2288	CTCAAGAAGATGTCGGAAAATCAC	*ptr-23* deletion screening primer, inner antisense
OG2289	ACCTGCAGCCGCTTCGACGA	*ptr-23* N-terminal gRNA
OG2290	ccacattggcgccgccacctgcagccgcttcgacgaaaaaaccatta attatatttctttttaacttctc	*ptr-23* deletion CRISPR HDR template
OG2291	ataagtttcgttcagaagtcctg	*ptr-23* deletion screening primer outer sense
OG2292	cctggattaagttgaaatacttc	*ptr-23* deletion screening primer inner sense
OG2302	actaatacatatatttttgattcattcaatattttgacgacttcttggataaattt atttttttcgcttt	*osm-8* deletion CRISPR HDR template
OG2366	ttccagataaatgccagccaaaatgttg	plasmid PCR for *dpy-7p:osm-8* promoter replacement, sense
OG2367	ttggtagggaatcatggtttttacctcctg	plasmid PCR for *dpy-7p:osm-8* promoter replacement, antisense
OG2368	aaaccatga ttccctaccaattgaaaattc	*dpy-7* promoter primer for osm-8 promoter replacement, sense
OG2369	tggctggcatttatctggaacaaaatgtaagaatattc	*dpy-7* promoter primer for osm-8 promoter replacement, antisense
OG2370	ttccagataaatggacgggagcatcgctc	*osm-8* plasmid PCR for *dpy-7p:ptr-23* promoter replacement, sense
OG2371	tcacctaaattgcgtttaaaccttcctgcag	*osm-8* plasmid PCR for *dpy-7p:ptr-23* promoter replacement, antisense
OG2372	tttaaacgcaatttaggtgacactatagaag	*dpy-7* promoter primer for *ptr-23* promoter replacement, sense
OG2373	tcccgtccatttatctggaacaaaatgtaagaatattc	*dpy-7* promoter primer for *ptr-23* promoter replacement, antisense
OG2374	GGAGAAGCTGGACGACTTCT	*osm-8* C-terminal gRNA
OG2375	acttcttagcaggcggagaagctggacgacttcttatgagtaaaggaga agaacttttcactg	*osm-8:sfGFP* repair primer, sense
OG2376	ttcacaaataatttaaagcgaaaaaaataaatttatcctttgtatagttcatc catgccatgtg	*osm-8:sfGFP* repair primer, antisense
OG2377	tttccagtagtgcaaataaatttaag	*osm-8:sfGFP* screening primer antisense

OG2378	tcaacaaaatactccaattggcgatg	*osm-8:sfGFP* screening primer sense
OG2379	AATGATATTTACATGTGTTC	*gpdh-2* C-terminal gRNA
OG2384	TTCTTCATCAACAAAATCGAAAACTAGAATTTCCT TAAATATCATTATAGGTTTCGCAAATTTCAATTAG	*gpdh-2* deletion repair oligo
OG2385	CAACTGCGCGCAGTGAATGCTGAG	*gpdh-2* deletion screening primer, sense
OG2386	GCTAGAACGAGGCATTGCACAGTGC	*gpdh-2* deletion screening primer, antisense

Figure legends

Figure 1 – *osm-8* physiological and behavioral phenotypes depend on *ptr-23*. A) Diagram of the *osm-8* and *ptr-23* alleles generated in this study. A detailed list of these and other strains can be found in Table 1. The *osm-8(n1518)* allele was characterized in a prior study (ROHLFING *et al.* 2011). B) Osmotic stress resistance (OSR) phenotype of the indicated genotypes. N=8 replicates per genotype (10 animals per replicate, N=80 per genotype). ****-p<0.0001, One-way ANOVA with Kruskal-Wallis post hoc test. Individual data points are shown along with the mean ± S.D. C) Osmotic avoidance phenotype of the indicated genotypes. N=8 replicates per genotype (10 animals per replicate, N=80 per genotype). ***-p<0.001, 'ns' – p>0.05, One-way ANOVA with Kruskal-Wallis post hoc test. Individual data points are shown along with the mean ± S.D. D) Osmotic avoidance phenotype of the indicated genotypes. N=8 replicates per genotype (10 animals per replicate, N=80 per genotype). **-p<0.01, 'ns' – p>0.05, One-way ANOVA with Kruskal-Wallis post hoc test. Individual data points are shown along with the mean ± S.D.

Figure 2 –*osm-8* mutants have normal ASH osmosensory neuron development and exhibit a distinct behavioral phenotype from the ciliary mutant *osm-6*. A) DiI staining of day 1 adults of the indicated genotypes. B) Latency to reversal response with 10% octanol. N= 98-136 individual trials per genotype. ****-p<0.0001, One-way ANOVA with Tukey's multiple comparison test. Individual data points are shown along with the mean ± S.D. C) Number of encounters with the hypertonic ring in the osmotic avoidance assay per individual animal. N=18-21 animals per genotype. ****-p<0.0001, One-way ANOVA with Tukey's multiple comparison test. Individual data points are shown along with the mean ± S.D. D) Time inside the hypertonic ring in the osmotic avoidance assay

per individual animal. N=18-21 animals per genotype. ****-p<0.0001, One-way ANOVA with Tukey's multiple comparison test. Individual data points are shown along with the mean ± S.D.

Figure 3 – *osm-8* and *ptr-23* hypodermal expression is necessary and sufficient to regulate osmotic avoidance behavior. A) Predicted expression of *osm-8*, *ptr-23*, and other Class 1 & 2 Osm mutants across sensory neurons and hypodermal cells adapted from the *C. elegans* neuronal gene expression map and network (CeNGEN) (TAYLOR *et al.* 2021) B) Osmotic stress resistance (OSR) phenotype of the indicated genotypes with *osm-8* or *ptr-23* rescue under either their endogenous promoter or the hypodermal specific promoter *dpy-7p*. N=8 replicates per genotype (10 animals per replicate, N=80 per genotype). ***-p<0.001, One-way ANOVA with Kruskal-Wallis post hoc test. Individual data points are shown along with the mean ± S.D. C) Osmotic avoidance phenotype of the indicated genotypes with *osm-8* or *ptr-23* rescue under either their endogenous promoter or the hypodermal specific promoter *dpy-7p*. N=8 replicates per genotype (10 animals per replicate, N=80 per genotype). ****-p<0.0001, *** – p<0.001, **-p<0.01, One-way ANOVA with Kruskal-Wallis post hoc test. Individual data points are shown along with the mean ± S.D. D) Osmotic stress resistance (OSR) phenotype of the indicated genotypes with empty vector or *ptr-23* RNAi. N=8 replicates per genotype (10 animals per replicate, N=80 per genotype). ***-p<0.001, **-p<0.01, One-way ANOVA with Kruskal-Wallis post hoc test. Individual data points are shown along with the mean ± S.D.. E) Osmotic avoidance phenotype of the indicated genotypes with empty vector or *ptr-23* RNAi. N=8 replicates per genotype (10 animals per replicate, N=80 per genotype). ****-p<0.0001, *-p<0.05, 'ns'-p>0.05, One-way ANOVA with Kruskal-Wallis post hoc test. Individual data points are shown along with the mean ± S.D.

Figure 4 – OSM-8 and PTR-23 co-localize in hypodermal lysosomes. A) Wide-field fluorescence images of L4 stage animals expressing A) *ptr-23::mSc*, B) *osm-8::mNG*, and C) the merged overlay the indicated endogenously tagged alleles. Scale bar = 10µm. Wide-field fluorescence images of day 1 adult animals expressing D) *ptr-23::mSc*, E) *osm-8::mNG*, and F) the merged overlay the indicated endogenously tagged alleles. Scale bar = 10µm. Wide field fluorescence images of Day 1 adults expressing G) the lysosomal marker *scav-3::sfGFP*, H) endogenously tagged *ptr-23:mSc*, and I) the merged overlay. Scale bar=10µm. Deconvolved wide field image of L4 stage animals expressing J) *osm-8::mNG*, K) the lysosomal marker *nuc-1:mCh*, and L) the merged overlay. Scale bar= 10µm. Dotted lines indicate the seam cell boundary, which lack OSM-8 expression.

Figure 5 – The lysosome-specific lipid bis(monoacylglyerol)phosphate (BMP) and cholesterol are upregulated in *osm-8* mutants in a *ptr-23* dependent manner. A) Heat map of the normalized log10 fold change for each indicated lipid class. Each column represents an individual replicate of 5,000 worms. AcCa=Acyl Carnitine, AEA=N-Acylethanolamine, BisMePE=Bis-methyl phosphatidylethanolamine, BMP=Bis(monoacylglyerol)phosphate, Cer=Ceramide, CerPE=Ceramide PE, Ch=Cholesterol, CL=Cardiolipins, Co=CoenzymeQ, DG=Diglycerides, Hex1Cer=Hexosylceramide, LPC=LysoPC, LPE=LysoPE, MG=Monoglycerides, OAHFA=OAcyl-(gamma-hydroxy)FA, PA=Glycerophosphatidic acid, PC=Glycerophosphocholines, PE=Glycerophosphoethanolamines, PFAA=Primary fatty acid amines, PG=Glycerophosphoglycerols, PI=Glycerophosphoinositols, PS=Glycerophosphoserines, SM=Sphingomyelins, TG=Triradylglycerols. B) Volcano plot

of the log_2 fold change versus log_{10} p-value for all identified lipid species in *osm-8(dr170)* compared to wild type (top) or *osm-8(dr170); ptr-23(dr180)* compared to wild type (bottom). BMP lipids, which are strongly upregulated in *osm-8(dr170)*, are highlighted in red. C) Normalized fold change for all BMP lipid species. Data shown are mean ± S.D. Lipids are organized as poly-unsaturated (>1 acyl chain double bonds) or mono-unsaturated (1 or 0 acyl chain double bonds). D) Normalized log_2 fold change for BMP lipid group in wild type, *osm-8(dr170)* and *osm-8(dr170); ptr-23(dr180)*. N=8 samples per genotype. Horizontal line indicates the mean. ****-p<0.0001, One-way ANOVA with Tukey post hoc test. E) Normalized log_2 fold change for phosphoglycerol lipid group in wild type, *osm-8(dr170)* and *osm-8(dr170); ptr-23(dr180)*. N=8 samples per genotype. Horizontal line indicates the mean. ****-p<0.0001, **-p<0.01, One-way ANOVA with Tukey post hoc test. F) Normalized log_2 fold change for triglyceride lipid group in wild type, *osm-8(dr170)* and *osm-8(dr170); ptr-23(dr180)*. N=8 samples per genotype. Horizontal line indicates the mean. ****-p<0.0001, ***-p<0.001, One-way ANOVA with Tukey post hoc test. G) Normalized log_2 fold change for phosphoglycerol lipid group in wild type, *osm-8(dr170)* and *osm-8(dr170); ptr-23(dr180)*. N=8 samples per genotype. Horizontal line indicates the mean. ****-p<0.0001, ***-p<0.001, **-p<0.01, One-way ANOVA with Tukey post hoc test.

Figure 6 – *osm-8* expands the pool of hypodermal lysosomes through a *ptr-23*-dependent, autophagy-independent mechanism. A) Deconvolved flattened Z-stacks of hypodermal *nuc-1:mCh* lysosomal fluorescence in day 1 adult animals of the indicated genotype. Scale bar = 5µm. B) Quantification of the number of *nuc-1:mCh* puncta in each genotype. Individual data points are shown along with the mean ± S.D.. N=18-21 measurements from 6-7 individual animals per genotype. ****-p<0.0001, 'ns'-not

significant, One-way ANOVA with Tukey post hoc multiple comparison testing. C) Widefield images of *lgg-1::gfp:mCh* autophagy marker in day 1 adults of the indicated genotype. Individual green puncta represent autophagosomes while red puncta represent autolysosomes. Scale bar = 5µm

Figure 7 – Mild physiological adaptation to osmotic stress drives a reversible Osm phenotype in wild type animals that is dependent on the V-ATPase subunit *vha-5.* A) Adaptation-induced osmotic avoidance behavior in day 1 wild type animals. Black symbols represent animals that were grown on 50mM NaCl and then shifted to 250mM NaCl for the indicated amount of time prior to performance of a standard Osm assay. Red symbols indicate animals that were grown on 250mM NaCl and then shifted back to 50mM NaCl for the indicated amount of time prior to the performance of a standard Osm assay. N=8 replicates per time point for adaptation and reversal (10 animals per replicate, N=80 per genotype). Data points are the mean ± S.D. ****-p<0.0001. ***-p<0.001, 'ns'-not significant versus t=0. One-way ANOVA with Dunnet's multiple comparison testing. B) Osmotic adaptation osmotic avoidance assay in wild type, *gpdh-1(dr154)*, *gpdh-2(dr195)*, and *gpdh-1(dr154); gpdh-2(dr195)* day 1 adult animals. N=8 replicates per genotype and per time point (10 animals per replicate, N=80 per genotype for each time point). 88-p<0.01, ***-p<0.001, ****-p<0.0001, One-way ANOVA with Tukey post hoc test. Individual data points are shown along with the mean ± S.D. C) Osmotic adaptation osmotic avoidance assay in wild type and *ptr-23(dr180)* day 1 adult animals. N=8 replicates per genotype and per time point (10 animals per replicate, N=80 per genotype for each time point). 'ns'-not significant, One-way ANOVA with Tukey post hoc test. Individual data points are shown along with the mean ± S.D. D) Osmotic adaptation osmotic avoidance assay in wild type, *vha-5(RNAi), osm-8(dr170),* and *osm-*

8(dr170); vha-5(RNAi) day 1 adult animals. N=8 replicates per genotype and per time point (10 animals per replicate, N=80 per genotype for each time point). ****-p<0.0001, ‘ns’-not significant, One-way ANOVA with Tukey post hoc test. Individual data points are shown along with the mean ± S.D. E) Survival of day 1 adults after 24 hour exposure to NGM plates with either 50mM NaCl or 250mM NaCl. N=4 replicates per condition (20-25 animals per replicate, 80-100 animals per condition per genotype). ****-p<0.0001, ‘ns’-not significant, One-way ANOVA with Tukey post hoc testing. Individual data points are shown along with the mean ± S.D. F) working model for the role of *osm-8*, *ptr-23*, and *vha-5* in the regulation of peripheral physiology and behavior.

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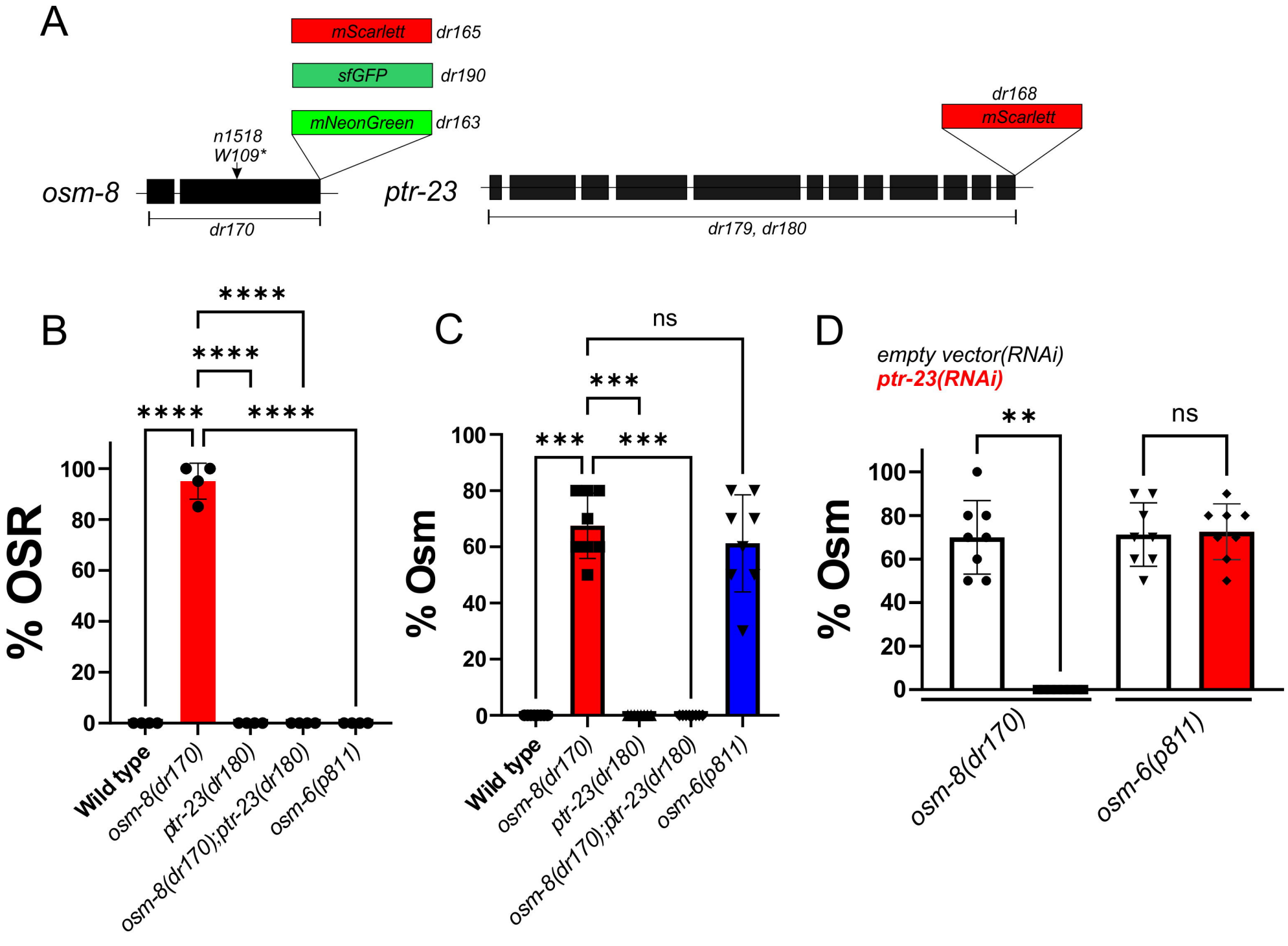
Figure 1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sfGFP
dr190
mNeonGreen
dr163
n1518
W109*
osm-8
dr170
ptr-23
dr168
mScarlett
dr179, dr180
B
% OSR
****
****
****
****
Wild type
osm-8(dr170)
ptr-23(dr180)
osm-8(dr170);ptr-23(dr180)
osm-6(p811)
C
% Osm
ns
***
***
***
Wild type
osm-8(dr170)
ptr-23(dr180)
osm-8(dr170);ptr-23(dr180)
osm-6(p811)
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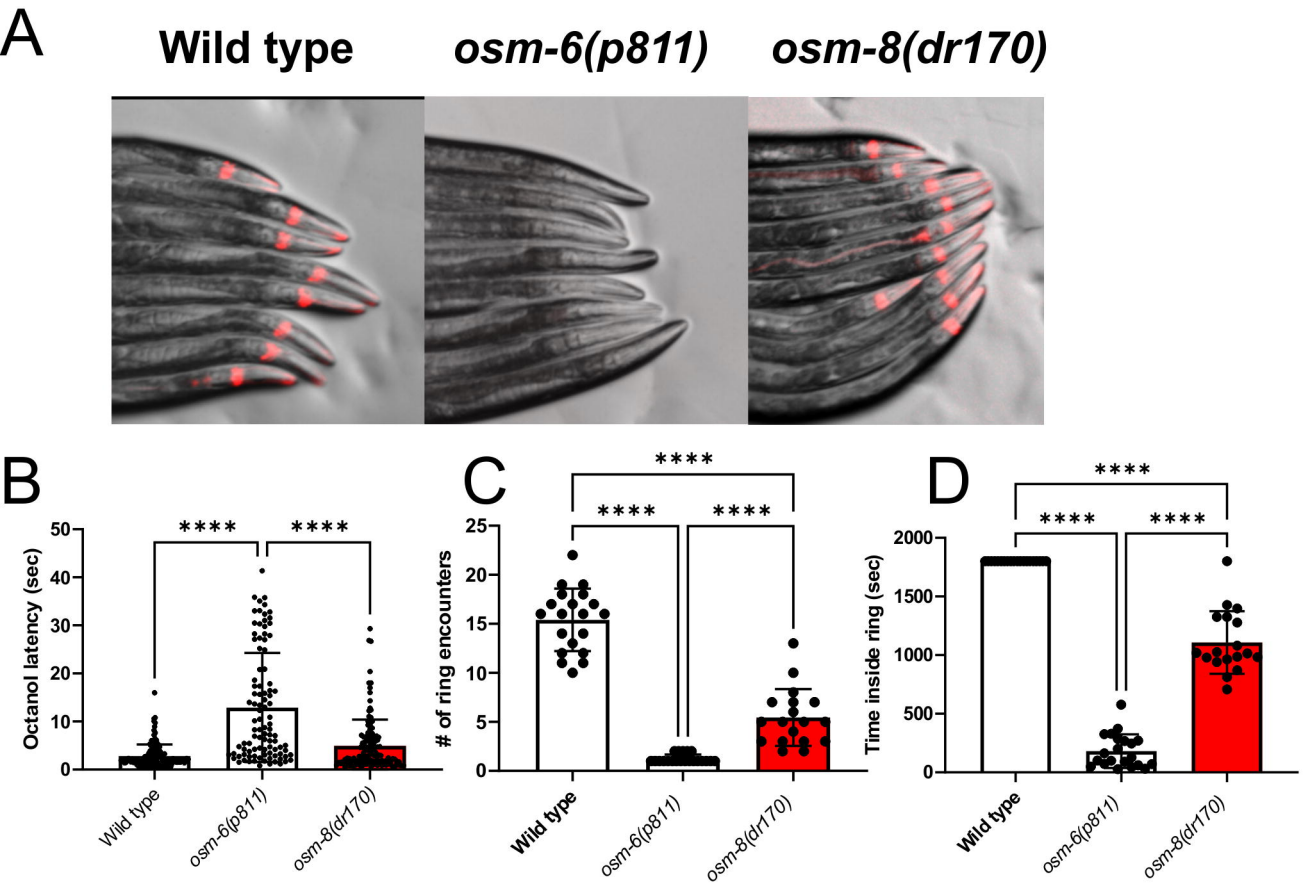
% Osm
empty vector(RNAi)
ptr-23(RNAi)
**
ns
osm-8(dr170)
osm-6(p811)

Figure 2


A
Wild type
osm-6(p811)
osm-8(dr170)
B
Octanol latency (sec)
50
40
30
20
10
0
****
****
Wild type
osm-6(p811)
osm-8(dr170)
C
# of ring encounters
25
20
15
10
5
0
****
****
****
Wild type
osm-6(p811)
osm-8(dr170)
D
Time inside ring (sec)
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1000
500
0
****
****
****
Wild type
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osm-8(dr170)

Figure 3

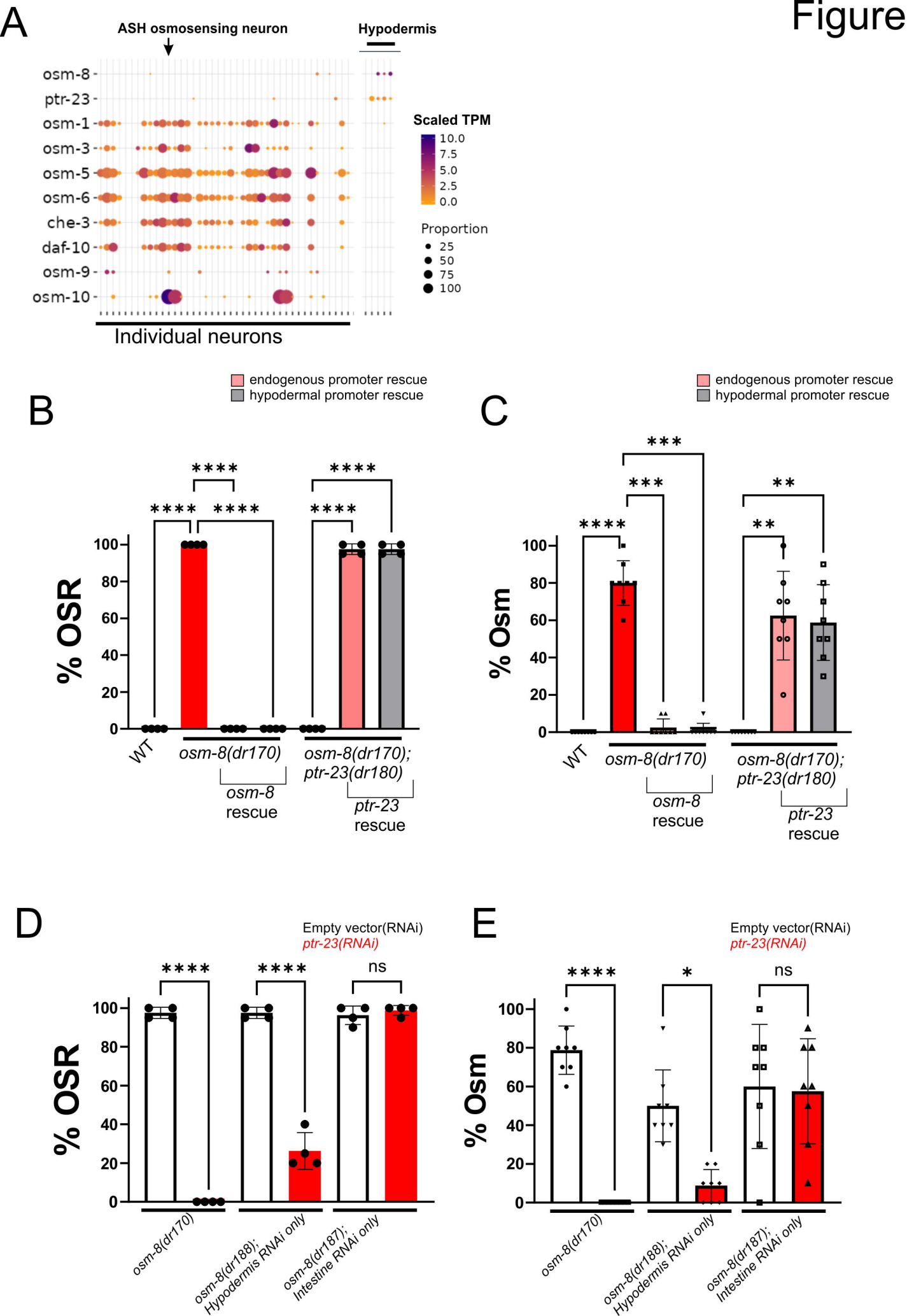
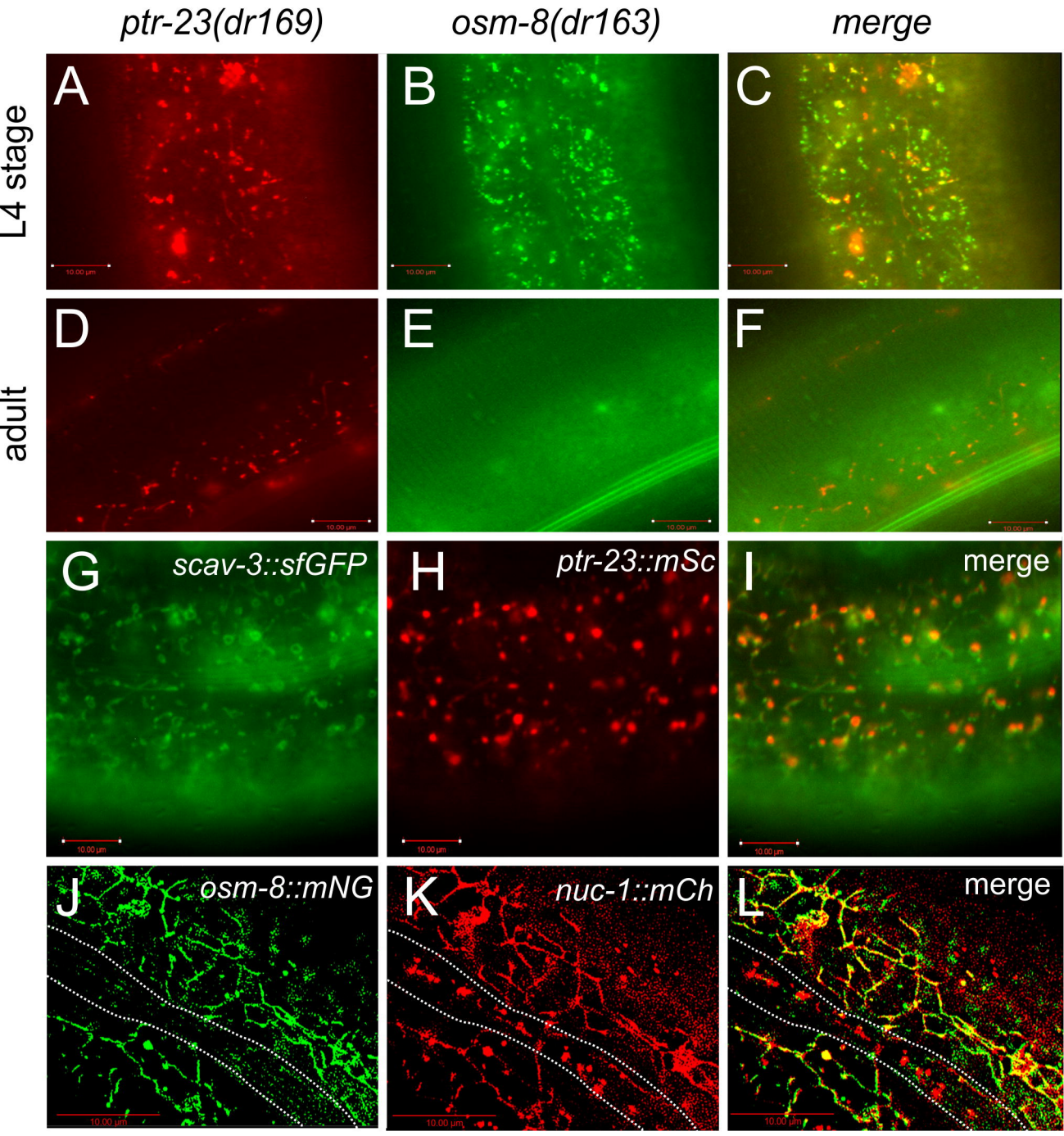

A
ASH osmosensing neuron
Hypodermis
osm-8
ptr-23
osm-1
osm-3
osm-5
osm-6
che-3
daf-10
osm-9
osm-10
Individual neurons
Scaled TPM
10.0
7.5
5.0
2.5
0.0
Proportion
25
50
75
100
B
endogenous promoter rescue
hypodermal promoter rescue
% OSR
WT
osm-8(dr170)
osm-8(dr170); ptr-23(dr180)
osm-8 rescue
ptr-23 rescue
C
% Osm
D
Empty vector(RNAi)
ptr-23(RNAi)
ns
osm-8(dr170)
osm-8(dr188); Hypodermis RNAi only
osm-8(dr187); Intestine RNAi only
E

Figure 4


ptr-23(dr169)
osm-8(dr163)
merge
L4 stage
adult
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B
C
D
E
F
G
scav-3::sfGFP
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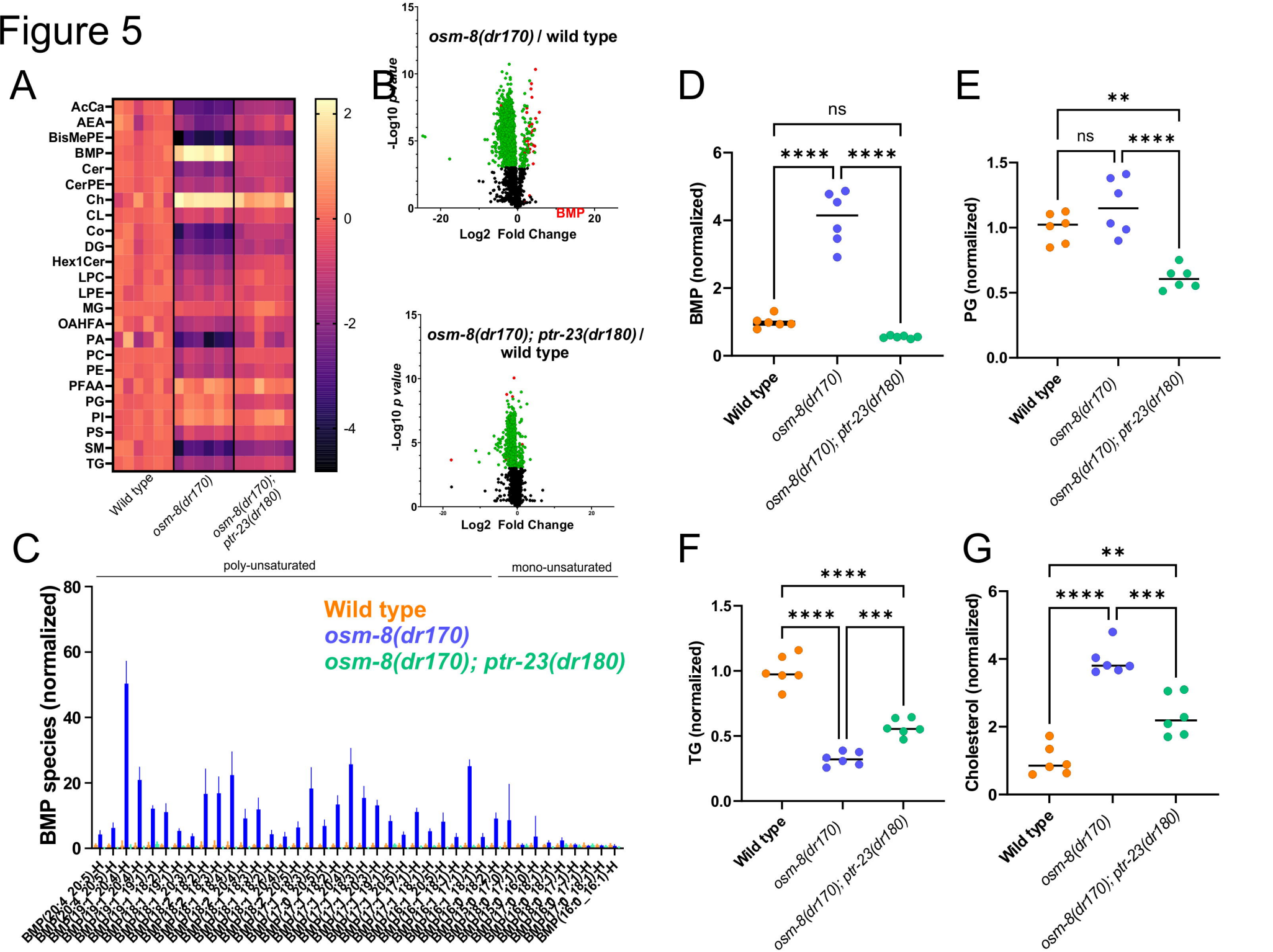
ptr-23::mSc
I
merge
J
osm-8::mNG
K
nuc-1::mCh
L
merge

Figure 5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MG
OAHFA
PA
PC
PE
PFAA
PG
PI
PS
SM
TG
Wild type
osm-8(dr170)
osm-8(dr170); ptr-23(dr180)
B
osm-8(dr170) / wild type
-Log10 p value
Log2 Fold Change
BMP
osm-8(dr170); ptr-23(dr180) / wild type
C
poly-unsaturated
mono-unsaturated
Wild type
osm-8(dr170)
osm-8(dr170); ptr-23(dr180)
BMP species (normalized)
D
BMP (normalized)
ns
****
E
PG (normalized)
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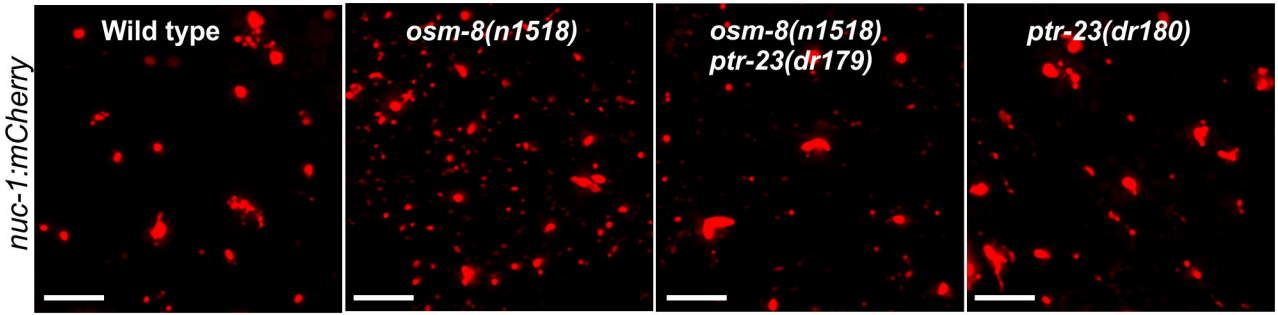
ns
****
F
TG (normalized)
****
***
G
Cholesterol (normalized)
**
****
***

Figure 6

A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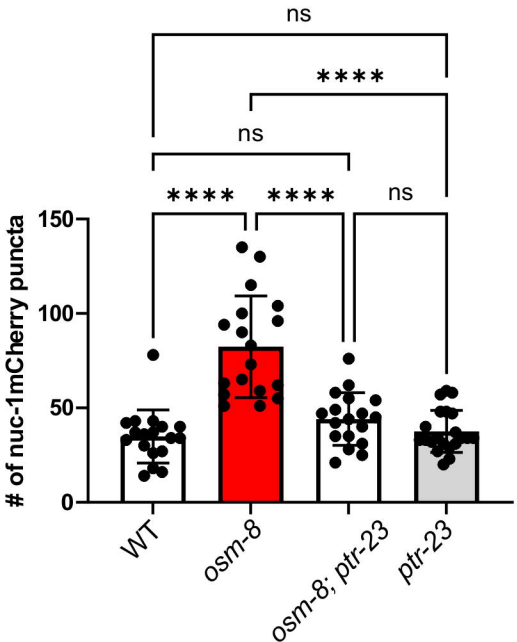
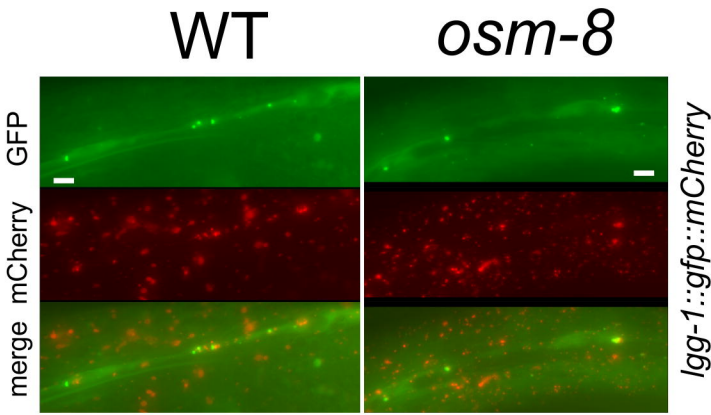
Wild type
osm-8(n1518)
osm-8(n1518)
ptr-23(dr179)
ptr-23(dr180)

B


ns
****
ns
****
****
ns
# of nuc-1mCherry puncta
150
100
50
0
WT
osm-8
osm-8; ptr-23
ptr-23

C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GFP
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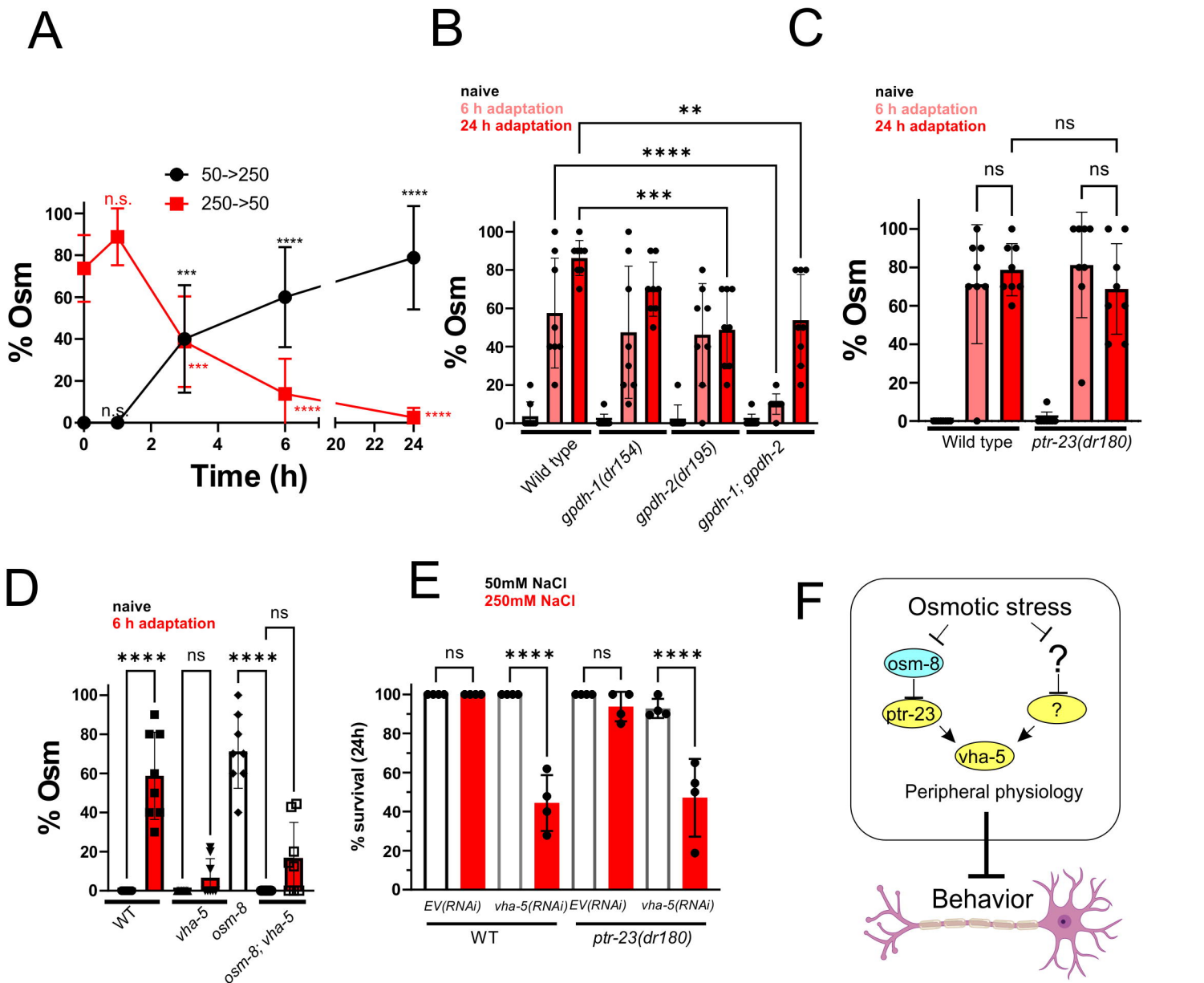
merge
lgg-1::gfp::mCherry

Figure 7


A
50->250
250->50
n.s.
***
****
% Osm
Time (h)
B
naive
6 h adaptation
24 h adaptation
**
****
***
% Osm
Wild type
gpdh-1(dr154)
gpdh-2(dr195)
gpdh-1; gpdh-2
C
naive
6 h adaptation
24 h adaptation
ns
% Osm
Wild type
ptr-23(dr180)
D
naive
6 h adaptation
****
ns
% Osm
WT
vha-5
osm-8
osm-8; vha-5
E
50mM NaCl
250mM NaCl
% survival (24h)
EV(RNAi)
vha-5(RNAi)
WT
ptr-23(dr180)
F
Osmotic stress
osm-8
ptr-23
?
vha-5
Peripheral physiology
Behavior