Temperature, Oxygen, and Salt-Sensing Neurons in C. elegans Are Carbon Dioxide Sensors that Control Avoidance Behavior

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SUMMARY

Homeostatic control of body fluid CO2 is essential in animals but is poorly understood. C. elegans relies on diffusion for gas exchange and avoids environments with elevated CO2. We show that C. elegans temperature, O2, and salt-sensing neurons are also CO2 sensors mediating CO2 avoidance. AFD thermo-sensors respond to increasing CO2 by a fall and then rise in Ca2+ and show a Ca2+ spike when CO2 decreases. BAG O2 sensors and ASE salt sensors are both activated by CO2 and remain tonically active while high CO2 persists. CO2-evoked Ca2+ responses in AFD and BAG neurons require cGMP-gated ion channels. Atypical soluble guanylate cyclases mediating O2 responses also contribute to BAG CO2 responses. AFD and BAG neurons together stimulate turning when CO2 rises and inhibit turning when CO2 falls. Our results show that C. elegans senses CO2 using functionally diverse sensory neurons acting homeostatically to minimize exposure to elevated CO2.

INTRODUCTION

As the major by-product of oxidative metabolism, CO2 is ubiquitous in nature. Although CO2 comprises only ~0.038% of Earth’s atmosphere, it can accumulate to higher levels in environments with high respiration rates (Lahiri and Forster, 2003). Organisms have evolved CO2-sensing mechanisms to monitor both external and internal CO2 concentrations, but how these systems function to control physiology and behavior remain poorly understood.

Mice can smell environmental CO2 at concentrations as low as 0.066% CO2 using specialized olfactory neurons that express carbonic anhydrase II (Hu et al., 2007). Carbonic anhydrases catalyze hydration of CO2 to generate H+ and HCO3−. HCO3− is thought to stimulate the mouse olfactory neurons by activating a guanylate cyclase, GC-D (Hu et al., 2007; Sun et al., 2009). In humans the GC-D homolog is a pseudogene, and we cannot smell CO2 (Young et al., 2007). However, we can taste CO2 in carbonated solutions via sour-sensing cells on our tongues (Chandra-shekar et al., 2009). In rodents, CO2 levels of 10% or more elicit an innate fear response in which animals freeze and avoid open spaces (Ziemann et al., 2009). This response requires activation of the acid-sensing ion channel ASIC-1A in cells of the amygdala (Ziemann et al., 2009). High concentrations of inhaled CO2 also modulate wakefulness by stimulating midbrain neurons (Williams et al., 2007; Richerson, 2004; Buchanan and Richerson, 2010).

In insects also sense and respond to environmental CO2. Drosophila adults and larvae avoid CO2 levels as low as 0.1% (Suh et al., 2004; Faucher et al., 2006). Like the CO2-evoked fear behavior in mice, Drosophila CO2 avoidance is innate (Suh et al., 2004) and may be part of an alarm response: stressed flies release 3- to 4-fold more CO2 than unstressed flies (Suh et al., 2004). Drosophila senses gaseous CO2 using two olfactory receptors, Gr21a and Gr63a, which are expressed in antennal sensory neurons (Jones et al., 2007; Kwon et al., 2007). Like other insect olfactory receptors, these do not have homologs in vertebrates or worms (Vosshall and Stocker, 2007). Artificial activation of the Gr21a/Gr63a-expressing neurons elicits an avoidance response (Suh et al., 2007). Whether the Gr21a/Gr63a receptor binds molecular CO2 or a CO2 derivative is not known. Interestingly, some food-associated odorants inhibit Gr21a/Gr63a CO2 receptor function, and the presence of food reduces CO2 avoidance (Turner and Ray, 2009). Although Drosophila avoids gaseous CO2, it is attracted to carbonated substrates, a response mediated by HCO3−-sensitive neurons in the proboscis (Fischler et al., 2007).

Besides monitoring external CO2, many animals also monitor internal CO2. Internal CO2 levels are regulated by respiratory gas exchange (Lahiri and Forster, 2003; Feldman et al., 2003; Bustami et al., 2002), but when left unregulated can lead to toxic changes in body fluid pH and death (Richerson, 2004). Mammalian respiratory CO2 chemoreception occurs in the brain and carotid bodies (Lahiri and Forster, 2003). The molecular mechanisms are unclear, but CO2-sensitive cells express carbonic anhydrases (Coates et al., 1998; Cammer and Brion, 2000), and changes in extracellular or intracellular pH modulate signaling via H+-sensitive ion channels (Lahiri and Forster, 2003; Richerson et al., 2005; Buckler et al., 2000; Feldman et al., 2003; Richerson, 2004; Jiang et al., 2005). Insects achieve respiratory gas exchange by opening and closing spiracles, but the control mechanisms involved are not known (Hetz and Bradley, 2005; Lehmann and Heymann, 2005).

Many small animals, including the nematode C. elegans, lack a specialized respiratory system and use diffusion for gas
exchange. As in other animals, high CO2 levels are toxic (Sharabi et al., 2009). C. elegans appears to control internal CO2 by avoiding environments where this gas exceeds ~0.5%. Avoidance requires cGMP-gated ion channels containing the TAX-2 and TAX-4 subunits (Bretscher et al., 2008; Hallem and Sternberg, 2008). Also implicated are the BAG sensory neurons, required for acute avoidance of a high CO2 and low O2 mixture (Hallem and Sternberg, 2008). Recent work indicates that the BAG neurons are transiently activated when ambient O2 levels fall below 10% (Zimmer et al., 2009).

Here, we show that the C. elegans head sensory neurons AFD, BAG, and ASE are primary CO2 sensors. AFD, BAG, and ASE were previously only known to detect changes in temperature, O2, and salt ion levels, respectively. Using Ca2+ imaging, we describe the CO2 responses of these neurons, which include ON, OFF, and perduring responses. We show that some, but not all, of the Ca2+ responses to CO2 depend on a cGMP-gated ion channel. Finally, we dissect how the C. elegans CO2 sensory system regulates CO2-evoked behavior. We find that the contribution of different sensors to behavior varies widely, depending on both context and stimulus dynamics.

RESULTS

Multiple Sensory Neurons Mediate C. elegans Avoidance of CO2

When placed in a 5%-0%-0% CO2 gradient, C. elegans migrate away from high CO2 (Figures 1A and 1B) (Bretscher et al., 2008). We used this assay to identify potential CO2-sensing sensors. Mutants defective in either the TAX-4 or TAX-2 β cGMP-gated ion channel subunits show reduced CO2 avoidance, both in the presence and absence of E. coli food (Figure 1C) (Bretscher et al., 2008; Hallem and Sternberg, 2008). The defects of tax-2; tax-4 double mutants recapitulated those of single mutants (Figure 1C), consistent with α and β subunits functioning together. tax-2 and tax-4 are coexpressed in 14 of 40 C. elegans sensory neuron classes (White et al., 1986; Komatsu et al., 1996; Coburn and Bargmann, 1996), implicating a subset of these neurons in CO2 sensing. A tax-2 promoter mutation, tax-2(p694), also disrupted CO2 avoidance (Figure 1C). Previous work reported that this allele deletes exon 1 and ~1.6 kb of tax-2 upstream sequences (Coburn and Bargmann, 1996). However, our sequencing data suggest that it removes only 365 bp in this interval (details in Supplemental Experimental Procedures available online). tax-2(p694) mutants have deficits in behaviors mediated by the AFD, BAG, ASE, AQR, PQR, and URX neurons but appear wild-type for responses mediated by other tax-2 expressing neurons (Dusenberg et al., 1975; Hedgcock and Russell, 1975; Coburn and Bargmann, 1996; Coates and de Bono, 2002). Selectively expressing tax-2 cDNA in AFD, BAG, ASE, AQR, PQR, and URX in tax-2(p694) mutants restored CO2 avoidance to the same extent as a full-length tax-2 genomic fragment (Figures 1C and 1D). We next attempted to rescue the tax-2 (p694) defect by expressing tax-2 cDNA from neuron-specific promoters, confirming appropriate expression by polycistronic constructs that coexpress tax-2 and gfp (Coates and de Bono, 2002). Expressing tax-2 cDNA in the AFD thermosensory neurons strongly rescued CO2 avoidance, both on and off food (Figure 1D). In contrast, restoring tax-2 to the BAG O2-sensing neurons rescued CO2 avoidance on food, as shown previously (Hallem and Sternberg, 2008), but not off food. Expressing tax-2 cDNA in the ASE taste neurons or in the AQR, PQR, and URX O2-sensing neurons also partially rescued CO2 avoidance, both on food and off food (Figure 1D). These data implicate functionally diverse sensory neurons in CO2 avoidance.

The AFD Thermosensory Neurons Sense CO2

The AFD neurons are transiently activated when temperatures exceed cultivation levels (Kimura et al., 2004; Clark et al., 2006). To test whether AFD also responds to CO2, we monitored AFD intracellular Ca2+ levels during CO2 exposure using the ratiometric Ca2+ sensor cameleon YC3.60, expressed in AFD under control of the gcy-8 promoter (Yu et al., 1997). Animals expressing the Ca2+ sensor retained wild-type CO2 responses (Figure S1A; see Experimental Procedures). To deliver CO2 stimuli, we used a Y-shaped microfluidic chamber that enables the gas phase over an immobilized animal to be switched in less than 3 s (Persson et al., 2009). In all experiments, O2 was maintained at 21%, with nitrogen (N2) completing the balance. AFD Left and AFD Right neurons responded equally to CO2 (Figure 2A; data not shown). On CO2 exposure the AFD neurons exhibited a fall in intracellular Ca2+ that slowly reversed to rise above baseline levels (“CO2-ON” response) within 2 min of CO2 coming on (Figures 2A and 2C). Thus, the AFD CO2-ON response has two components to it, an “ON-minimum” and an “ON-maximum.” Strikingly, AFD also responded to removal of CO2 with a fast Ca2+ spike that peaked within 10 s (“CO2-OFF” response, Figures 2A and 2D). The OFF-maximum was the largest feature of the AFD Ca2+ pattern, being on average 3- to 4-fold greater than the ON-maximum (Figure 2B). All three components of the AFD CO2 response were concentration dependent (Figure 2B). To exclude the possibility that the observed activity could be due to AFD temperature sensing, we exposed animals to 0%-0%-0% CO2 mock switches. Under these conditions AFD gave no responses (first 9 min, Figure 2E).

We next examined whether repeated stimulation altered AFD Ca2+ responses. Some C. elegans sensory neurons, such as the ALM anterior touch neurons, habituate upon repeated stimulation (Kindt et al., 2007). The AFD OFF response remained undiminished upon repeated exposure to 3% CO2 (Figures 2E, 2F, and S1B). We also asked whether prolonged CO2 exposure affects AFD responses. After a 9 min exposure to 3% CO2, the ON-maximum had decayed to baseline levels, whereas the OFF-maximum was unaltered (Figure 2G). CO2-evoked activity in AFD could be due to synaptic input to AFD. To test this, we imaged CO2 responses in unc-13 mutants, which have severe defects in synaptic release (Richmond et al., 1999). The AFD CO2 responses of unc-13 animals were indistinguishable from wild-type (Figures 2H and S1C). These data suggest that, as well as being a thermosensory neuron (Mori and Ohshima, 1995; Kimura et al., 2004; Clark et al., 2007), AFD is a CO2 sensor with both ON and OFF responses. The sensory endings of AFD have many finger-like projections, potentially providing a large surface for CO2 and temperature reception (Ward et al., 1975).
AFD only responds to a temperature rise above the cultivation temperature (Kimura et al., 2004; Clark et al., 2006). If AFD temperature and CO₂-sensing are distinct, AFD might be expected to respond to CO₂ at temperatures below the cultivation temperature. To test this, we built a temperature-controlled stage (see Supplemental Experimental Procedures). In animals grown at 22°C, AFD responded to CO₂ both at 15°C and at 22°C (Figures S1E and S1F). The shape of the response was similar at the two temperatures but smaller at 15°C than at 22°C. These data support the idea that AFD CO₂ and temperature-sensing pathways are at least partly distinct.

The BAG O₂ Sensory Neurons

Sense CO₂

Recent work has shown that the BAG neurons are transiently activated when O₂ levels drop below 10% (Zimmer et al., 2009). Hallem and Sternberg (2008) showed that feeding animals lacking the BAG neurons have reduced avoidance of a 10% CO₂ /10% O₂ mixture. We have previously shown that O₂ responses can modulate CO₂ avoidance (Bretscher et al., 2008). These data suggest that either BAG responds exclusively to O₂ but modulates neural circuits mediating CO₂ responses or that BAG is a primary sensor of both O₂ and CO₂.

To test BAG neuron CO₂ mediation, we created animals expressing cameleon YC3.60 in BAG from a pflp-17;YC3.60 transgene and imaged Ca²⁺ levels. The BAGL and BAGR neurons were exquisitely sensitive to a rise in CO₂ (Figures 3A–3C). Cameleon reported a rise in Ca²⁺ that peaked after ~30 s and then decayed (Figures 3A and 3B). The excitability threshold of BAG was below 0.25% CO₂. A plot of mean fluorescence ratio

Figure 1. The cGMP-Gated Ion Channel Subunit TAX-2 Acts in Multiple Neurons to Promote CO₂ Avoidance

(A and B) Wild-type C. elegans distribute uniformly in air (A) but avoid 5% CO₂ (B) over 10 min. N_L and N_R, the number of animals in the left and right halves of the chamber, respectively.

(C) Mutations in the cGMP-gated ion channel subunits tax-2 and tax-4 disrupt avoidance of 5% CO₂ both on and off food. The null allele tax-2(ot25) and promoter deletion allele tax-2(p694) almost completely abolish CO₂ avoidance. A transgene containing tax-2 genomic DNA restores CO₂ avoidance to tax-2(p694) mutants. In this and all subsequent figures, unless otherwise stated: a 5%-0% CO₂ gradient was used; data points represent an average of nine assays; error bars indicate standard error of the mean (SEM); ns, not significantly different; *** or +++ indicates p < 0.001; ** or ++ indicates p < 0.01; * or + indicates p < 0.05; and significance comparisons were made using the two-tailed Student’s t test.

(D) Expressing full-length tax-2 cDNA in the AFD, BAG, ASE, and AQR, PQR, and URX neurons rescues CO₂ avoidance in tax-2(p694) mutants. Expressing tax-2 cDNA from the neuronal-specific promoters pfgcy-8 (AFD), pflp-17 (BAG), and an ASE-specific pflp-6 fragment or pfgcy-32 (AQR, PQR, URX) gives varying degrees of rescue. Significance comparison of the transgenic line expressing tax-2 in all six neurons is with N₂. For all other genotypes, significance markers indicate comparison with tax-2(p694).
Figure 2. The AFD Thermosensory Neurons Sense CO2
(A) Mean fluorescence ratio (YFP/CFP) of AFD neurons expressing cameleon YC3.60 across a 0%-1%-0%-3%-0%-5%-0% CO2 stimulus. In this and all subsequent figures, blue shading indicates presence of CO2, and gray shading indicates the SEM (n = 26 traces).

(B) Mean ratio change, ΔR, expressed as a percentage of the initial fluorescence ratio, R0, for the AFD ON and OFF responses for mock, 1%, 3%, and 5% CO2 concentrations. ΔR = Rf – R0, where R0 is the fluorescence ratio after gas shift. Time intervals for calculation of R0 and corresponding intervals for Rf were chosen according to peaks in ratio change. For ON-minima, a 20 s time interval was used, for ON-maxima a 30 s interval, and for OFF-maxima an 8 s interval. Data for 1%, 3%, and 5% steps from (A); data for mock step from (E). Details for 1%, 3%, and 5% steps: ON-minima (150–170 s and 190–210 s, 510–530 s, and 550–570 s, 870–890 s and 910–930 s, used for R0 and Rf respectively); ON-maxima (150–180 s and 330–360 s, 510–540 s, and 690–720 s, 870–900 s, and 1050–1080 s, used for R0 and Rf respectively); OFF-maxima (344–352 s and 364–376 s, 704–712 s and 728–736 s, 1064–1072 s and 1088–1096 s, used for R0 and Rf respectively). Significance markers indicate comparisons with responses to a mock 0% CO2 gas switch. Error bars indicate SEM.

(C) Expanded view of mean AFD response to a 0%-3% CO2 increase (C) and 3%-0% CO2 decrease (D). Data for 1%, 3%, and 5% steps from (A); data for mock step from (E). Details for 1%, 3%, and 5% steps: ON-minima (150–170 s and 190–210 s, 510–530 s, and 550–570 s, 870–890 s and 910–930 s, used for R0 and Rf respectively); ON-maxima (150–180 s and 330–360 s, 510–540 s, and 690–720 s, 870–900 s, and 1050–1080 s, used for R0 and Rf respectively); OFF-maxima (344–352 s and 364–376 s, 704–712 s and 728–736 s, 1064–1072 s and 1088–1096 s, used for R0 and Rf respectively). Significance markers indicate comparisons with responses to a mock 0% CO2 gas switch.

(D) Mean ratio change, ΔR, expressed as a percentage of the initial fluorescence ratio, R0, for the AFD ON and OFF responses for mock, 1%, 3%, and 5% CO2 concentrations. ΔR = Rf – R0, where R0 is the fluorescence ratio after gas shift. Time intervals for calculation of R0 and corresponding intervals for Rf were chosen according to peaks in ratio change. For ON-minima, a 20 s time interval was used, for ON-maxima a 30 s interval, and for OFF-maxima an 8 s interval. Data for 1%, 3%, and 5% steps from (A); data for mock step from (E). Details for 1%, 3%, and 5% steps: ON-minima (150–170 s and 190–210 s, 510–530 s, and 550–570 s, 870–890 s and 910–930 s, used for R0 and Rf respectively); ON-maxima (150–180 s and 330–360 s, 510–540 s, and 690–720 s, 870–900 s, and 1050–1080 s, used for R0 and Rf respectively); OFF-maxima (344–352 s and 364–376 s, 704–712 s and 728–736 s, 1064–1072 s and 1088–1096 s, used for R0 and Rf respectively). Significance markers indicate comparisons with responses to a mock 0% CO2 gas switch. Error bars indicate SEM.

(E) Mean AFD response to multiple 3% CO2 stimuli (E) and individual responses (F) plotted in a heat map (n = 9 traces).

(F) Mean AFD response to multiple 3% CO2 stimuli (E) and individual responses (F) plotted in a heat map (n = 9 traces).

(G) Mean AFD response to a 3% CO2 stimulus lasting 9 min (n = 9 traces).

(H) Mean AFD response to 3% CO2 in an unc-13 mutant.

To test if the BAG neurons are primary CO2 sensors, we disrupted synaptic input to BAG using the unc-13 and unc-31 mutations. unc-31 mutants are defective in dense-core vesicle release, but not synaptic vesicle release (Speese et al., 2007). Neither the unc-13 nor the unc-31 mutations disrupted BAG Ca2+ responses, suggesting that BAG neurons are intrinsically CO2 sensitive (Figures 3I–3K). However, the magnitude of Ca2+ responses in these mutants was significantly enhanced, particularly in unc-31 animals, suggesting that BAG activity is normally inhibited by neuromodulators.

The Asymmetric ASEL and ASER Taste Neurons Are Both Activated by CO2
We next examined CO2 responses in the ASE neurons that mediate chemotaxis to water-soluble cues, including salt ions such as Na+ and Cl− (Bargmann and Horvitz, 1991; Ortiz et al., 2009). ASEL and ASER are functionally asymmetric (Hobert et al., 2002). ASEL is activated by a rise in the concentration of NaCl,
whereas ASER is activated by a drop (Suzuki et al., 2008). For NaCl responses, activation of ASEL inhibits animals from reversing, whereas activation of ASER increases reversal likelihood (Suzuki et al., 2008).

We imaged ASEL and ASER Ca\textsuperscript{2+} responses to CO\textsubscript{2}, using animals expressing the Ca\textsuperscript{2+} sensor YC2.12 in ASE from a pflp-6::YC2.12 transgene (Suzuki et al., 2008). Both ASEL and ASER were activated by 1%, 3%, and 5% CO\textsubscript{2} (Figures 3A-C, D). The mean fluorescence ratio change, ΔR/R\textsubscript{0}, is plotted as a percentage of the mean baseline fluorescence ratio, R\textsubscript{0}. ΔR = R\textsubscript{f} – R\textsubscript{0}; R\textsubscript{f} was calculated from the peak of the BAG Ca\textsuperscript{2+} response at 200–260 s and R\textsubscript{0} from 120–180 s. Curve fit of the standard equation for a single-site binding process (Michaelis-Menten, y = V\textsubscript{max}x/(K\textsubscript{d} + x), where V\textsubscript{max} and K\textsubscript{d} are constants with units of [% mean ratio change] and % CO\textsubscript{2}, respectively) to the red data points using least-squares regression analysis. The blue data point (10% CO\textsubscript{2}) was omitted from the curve fit because at 10% CO\textsubscript{2} the BAG fluorescence ratio (YFP/CFP) falls outside of the linear dynamic range of the Ca\textsuperscript{2+} sensor YC3.60. Curve fit gives K\textsubscript{d} = 2.9% CO\textsubscript{2}, and V\textsubscript{max} = 166% mean ΔR/R\textsubscript{0}, with a goodness of fit R\textsuperscript{2} regression value of 0.995. Error bars indicate SEM.

We also measured BAG responses to a 0%-3%-0%-3%-0%-3%-0%-3%-0%-3%-0% CO\textsubscript{2} stimulus lasting 18 min (n = 9 traces) (Figures 3F-H). BAG responses to a 0%-3%-0%-3%-0%-3%-0%-3%-0%-3%-0% CO\textsubscript{2} stimulus were plotted in a heat map (Figures 3H, I, J), and individual BAG Ca\textsuperscript{2+} traces are plotted in a heat map (Figures 3H, I, J). Mean percent (% ΔR/R\textsubscript{0}) values for (I) and (J) are shown (n = 6 traces). Asterisks indicate significance compared to wild-type.

We also measured BAG responses in unc-13 mutants (I) and unc-31 mutants (J). We measured mean percent (% ΔR/R\textsubscript{0}) values for (I) and (J), and individual BAG Ca\textsuperscript{2+} traces are plotted in a heat map (Figures 3H, I, J). Asterisks indicate significance compared to wild-type.
4A–4E), although the responses of ASEL were generally ~2-fold larger than those of ASER (Figure 4E). ASEL and ASER responses to CO₂ were slow, taking around 2 min for Ca²⁺ levels to peak (Figure 4F). Sustained elevated CO₂ led to sustained increases in Ca²⁺ (Figure 4F). As for AFD and BAG, ASE neurons appeared to be intrinsically CO₂ sensitive because Ca²⁺ responses were intact in unc-13 mutants (Figures 4G and S1D).

In summary, ASEL and ASER both respond to CO₂ by a slow rise in Ca²⁺ that persists while CO₂ is high and returns to baseline when CO₂ returns to baseline.

**AQR, PQR, and URX O₂-Sensing Neurons Are Weakly CO₂ Responsive**

We examined whether the AQR, PQR, and URX O₂-sensing neurons (Persson et al., 2009; Zimmer et al., 2009) respond to CO₂ because our tax-2 rescue data indicated that these neurons contribute, albeit weakly, to CO₂ avoidance. Average Ca²⁺ traces indicated that unlike AFD, BAG, and ASE, none of these neurons respond reliably to CO₂ (Figures S2A–S2D). URX most consistently showed CO₂-evoked activity, and this was retained in unc-13 mutants (Figures S2A, S2E, and S2F). AQR and PQR occasionally showed a Ca²⁺ rise associated with an increase in CO₂ but also showed apparent spontaneous activity that lay out of synchrony with the CO₂ stimulus (Figures S2B–S2D). The response of PQR to a 0%-3%-0%-3% CO₂ stimulus was dwarfed by its response to a 21%-11%-21%-11% O₂ stimulus (Figure S2C).

Having identified three C. elegans neuron classes that responded strongly to CO₂ and a further three that responded weakly to CO₂, we considered the possibility that all sensory neurons show some CO₂ responsiveness. Therefore, we imaged
Ca$^{2+}$ responses to CO$_2$ in the ASH neurons that respond to various aversive stimuli (Hillard et al., 2005). ASH showed no response to 3% CO$_2$ (Figure 4H). This suggests that AFD, BAG, and ASE are functionally specialized as CO$_2$ sensors.

**CO$_2$ Sensitivity in BAG and AFD Requires a cGMP-Gated Ion Channel**

Our tax-2 rescue data suggested that CO$_2$ sensing in BAG and AFD neurons involves cGMP signaling. To examine this further we imaged BAG responses to CO$_2$ in tax-2(p694) and tax-4 (null) mutants. Both mutations completely abolished CO$_2$-evoked Ca$^{2+}$ responses in BAG (Figures 5A and 5C). This suggests that BAG CO$_2$ sensory transduction is mediated by TAX-2/TAX-4 cGMP-gated channels and by extension, upstream guanylate cyclases (gcys).

The only gcys genes known to be expressed in BAG are the atypical soluble guanylate cyclases gcy-31 and gcy-33 (Yu et al., 1997; Zimmer et al., 2009; Ortiz et al., 2006). These appear to be O$_2$ regulated (Gray et al., 2004; Boon and Marletta, 2005) because both are required for BAG O$_2$ responses (Zimmer et al., 2009). To examine if GCY-31, GCY-33, or both are required in CO$_2$ sensory transduction, we imaged BAG responses to 3% CO$_2$ in gcy-31; gcy-33 double-deletion mutants. Loss of gcy-31 and gcy-33 reduced the CO$_2$-evoked BAG Ca$^{2+}$ response (Figures 5B and 5C). This suggests that GCY-31 and/or GCY-33 forms part of the CO$_2$ sensory system in BAG, although other molecules are likely to be involved.

We next imaged AFD responses in tax-2(null) and tax-2(p694) animals. Expression from the gcy-8 promoter is markedly reduced in tax-2 and tax-4 mutants (Satterlee et al., 2004), and YC3.60 expression was correspondingly low in AFD in tax-2 (ot25null) animals. In contrast, expression in tax-2(p694) animals was similar to wild-type (data not shown). Both tax-2 mutations significantly reduced the AFD CO$_2$ response, but neither completely abolished it (Figures 5D–5F). The AFD ON-minimum appeared to be absent in both tax-2 mutants, whereas the AFD...
ON-maximum was absent in *tax-2*(*null*) animals but enhanced in *tax-2*(p694) animals (Figures 5D–5F). Our data suggest that all three components of the AFD CO₂ response involve TAX-2-mediated cGMP pathways but that other pathways also contribute.

**C. elegans** Carbonic Anhydrases Are Expressed in Several Neurons, Including BAG

To further investigate molecular mechanisms of CO₂ sensing, we asked whether *C. elegans* CO₂ sensors express carbonic anhydrases, hallmarks of CO₂-responsive neurons in other animals (Hu et al., 2007; Wang et al., 2002; Ridderdzle and Hanson, 1985; Coates et al., 1998). Database searches indicate that the *C. elegans* genome encodes eight predicted carbonic anhydrases. Six, *cah-1* to *cah-6*, belong to the alpha family, and two, *bca-1* and *bca-2*, to the beta family. Because many members of the beta family are mitochondrial (Syrjänien et al., 2010; Fasseas et al., 2010), we focused our studies on the alpha family. We fused upstream promoter regions of each gene to gfp and examined the resulting expression patterns. We found that *cah-1*, *2*, *3*, and *6* show strong neuronal expression in adults (Figure S3A). *cah-4* was primarily expressed in the hypodermis (excluding the seam cells) and in the excretory cell, consistent with a kidney-like function for this cell. *cah-3* and *cah-5* show expression in intestinal cells, with *cah-3* expression being especially strong. Using a *pBAG::mCherry* marker, we showed that *cah-2*, but not apparently any of the other five *cah* genes, was expressed in BAG (Figure S3B). *cah-2* was also expressed in a set of four quadrant head neurons, other unidentified head neurons, the canal neurons CANL/R, whose processes run parallel to the tracts of the excretory cell, and a pair of tail neurons (Figure S5). Previous data suggest that *cah-2* is also expressed in AFD (Colosimo et al., 2004). These data suggest that BAG and AFD neurons are specialized CO₂ sensors that coexpress carbonic anhydrases and CO₂-regulated cGMP pathways. They also raise the possibility that other *C. elegans* neurons and tissues respond to CO₂.

**AFD and BAG Direct Avoidance Behavior in Spatial CO₂ Gradients**

To investigate how CO₂ sensors contribute to avoidance in spatial gradients, we genetically ablated neurons. We focused on AFD and BAG neurons because the Ca²⁺ responses of ASE to CO₂ stimuli were slow, and those of AQR, PQR, and URX, weak. Specification of the AFD neurons requires the *otd/Otx* homeodomain transcription factor *txx-1*, which is expressed only in AFD (Satterlee et al., 2001). *txx-1* mutants show thermotactic defects equivalent to those of animals in which AFD has been removed by laser ablation (Mori and Ohshima, 1995). *txx-1* mutants had a strong CO₂ avoidance defect off food, and a weaker defect on food (Figure 5G). Wild-type avoidance was restored to *txx-1* mutants by a transgene containing *txx-1* genomic DNA (Figure 5G). These data suggest that the AFD neurons promote CO₂ avoidance in spatial CO₂ gradients.

To ablate BAG we expressed the *egl-1* programmed cell death activator from a BAG-specific *gcy-33* promoter (Conradt and Horvitz, 1998; Yu et al., 1997) (we thank M. Beverly and P. Sengupta for this line). Both BAGL and BAGR neurons were absent in greater than 90% of animals bearing this transgene (Table S1 available online). Surprisingly, the CO₂ avoidance of BAG-ablated animals was not significantly different from wild-type, both on and off food (Figure 5G). We asked if combined genetic ablation of AFD and BAG causes a synthetic CO₂ avoidance phenotype. Ablating the BAG neurons disrupted the residual CO₂ avoidance of *txx-1*(p767) mutants on food (Figure 5G). However, in the absence of food, *txx-1*(p767); *pgcy-33::egl-1* animals showed no greater defect than *txx-1*(p767) single mutants (Figure 5G). These data show that AFD and BAG promote CO₂ avoidance in spatial gradients on food, and that AFD and at least one other neuron that is not BAG promote avoidance when food is absent. Thus, the importance of different sensory neurons for CO₂ avoidance in spatial gradients depends on context.

**AFD and BAG Control Discrete Aspects of the C. elegans Response to CO₂**

In 5%-0% CO₂ spatial gradients (Figure 1), a *C. elegans* moving at ~0.3 mm/s experiences a change of 0%-0.05% CO₂/s, depending on bearing relative to the gradient. In our Ca²⁺-imaging experiments, immobilized animals experienced much sharper temporal gradients of ~1% CO₂/s. In the wild, animals are likely to encounter a variety of CO₂ gradients. To analyze behavioral responses to sharp CO₂ gradients, we designed a square-shaped microfluidic chamber that enables CO₂ levels over freely moving animals to be switched rapidly (Movie S1 available online). We recorded responses and used custom software to extract instantaneous speed, reversal rate, and rate of omega turns, in which an animal’s head and tail touch to form an “Ω” shape (N2, Figure 6B). In the absence of food, a rise in CO₂ from 0% to 5% elicited a brief slowing followed by a transient increase in reversals and omega turns (Figure 6B). A rapid drop in CO₂, from 5% to 0%, elicited an acceleration that coincided with suppression of reversals and omega turns.

The timing of CO₂-evoked Ca²⁺ responses in both AFD and BAG correlated with peaks in locomotory activity (Figure 6A). We investigated these correlations directly by ablating AFD and/or BAG and examining behavioral responses (Figure 6B). For statistical comparison, we chose time intervals before and after gas switches according to the occurrence of peaks in wild-type behavioral rates. In the absence of food, neither AFD nor BAG ablation abolished modulation of speed across shifts in CO₂ (Figures 6B and S4). Stronger phenotypes were observed for reversal and omega rates (Figure 6B). Unexpectedly, ablation of AFD increased reversal and omega rates following a sharp
CO2 rise (ttx-1, Figures 6B, 7C, 7H, and 7I) and reduced suppression of omega turns following a CO2 fall (ttx-1, Figures 6B, 7K, and 7L), suggesting that AFD acts to suppress reversals and omega turns at these two time points. Ablation of BAG abolished reversal and omega responses to a rise in CO2 (pBAG::egl-1, Figures 6B, 7B, 7C, 7H, and 7I) and reduced the suppression of omega turns following a CO2 fall (pBAG::egl-1, Figures 6B, 7K, and 7L), consistent with BAG excitation promoting reversals and omega turns. Coablation of AFD and BAG abolished the suppression of reversals and omega turns following a fall in CO2 (ttx-1; pBAG::egl-1, Figures 7F and 7L). This effect was due to reduced reversal and omega rates under prolonged...
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**CO₂ Sensing in C. elegans**

high CO₂ (ttx-1; pBAG::egl-1, red bars, Figures 7E and 7K). These data suggest that together BAG and AFD act to suppress reversals and omega turns when CO₂ decreases.

Curiously, AFD-ablated BAG-ablated animals continued to show a transient increase in reversals following a CO₂ rise (ttx-1; pBAG::egl-1, Figures 6B, 7B, and 7C). This result suggests that there is at least one other CO₂ “ON” sensory neuron, XYZ, that promotes reversals in response to a CO₂ rise. It also suggests that after a CO₂ rise, AFD acts antagonistically to both BAG and the hypothetical XYZ neuron to inhibit reversals.

We investigated whether the ASE or AQR, PQR, URX neurons could be XYZ by ablating them together with AFD and BAG. Ablating ASEL/R had no significant effect on the reversal rate of AFD-ablated BAG-ablated animals immediately following a CO₂ rise (che-1; ttx-1; pBAG::egl-1, Figures S5A–S5D) but did alter reversal rates under prolonged high CO₂ (Figures S5E and S5F). The ablation of AQR, PQR, URX by an integrated pgcy-36::egl-1 transgene caused an increase in the reversal rate of AFD-ablated BAG-ablated animals in air alone (Figures S5A–S5D). These data suggest that the ASE neurons suppress reversals under prolonged high CO₂ and that the AQR, PQR, URX neurons suppress reversals in the absence of CO₂. However, even animals defective in AFD, BAG, ASE, AQR, PQR, and URX retained some CO₂ responsiveness, suggesting that C. elegans has additional CO₂ sensors.

**The Presence of Food Modulates the Neural Circuit Controlling CO₂ Avoidance**

Wild-type C. elegans (N2) exhibit distinct locomotory patterns in the presence and absence of food (de Bono and Bargmann 1998; Sawin et al., 2000). Animals move slowly and reverse frequently on food, whereas in its absence they move rapidly with fewer reversals. The escape mechanisms elicited by a CO₂ rise on and off food were correspondingly different (Movies S1 and S2 and Figure S6). Feeding animals still briefly slowed down when CO₂ levels rose but then switched to a much stronger transient increase in omega turns (Figure S6). Feeding animals also persistently suppressed reversals in high CO₂. These mechanisms increased the exploratory behavior of feeding animals, presumably helping them to escape from high CO₂.

To investigate whether AFD and BAG contribute to differences between on- and off-food behavior, we ablated them. AFD ablation abolished the increased speed response to high CO₂ and resulted in an inappropriately high-reversal and omega rates under high CO₂ (ttx-1, Figure S6). In contrast, ablating only BAG had little or no effect (pBAG::egl-1, Figure S6). Abblating neither AFD nor BAG alone abolished the dramatic spike in omega turns following a CO₂ rise, but ablating both neurons together nearly did (ttx-1; pBAG::egl-1, Figure S6). As for off food, loss of AFD and BAG did not eliminate CO₂ responses, suggesting that other neurons contribute to rapid CO₂-evoked behavior on food.

In summary, genetic ablation suggests that AFD and BAG account for much of the different behavioral strategies employed in CO₂ avoidance on and off food. In both contexts one or more other neurons also contribute to CO₂ avoidance.

**DISCUSSION**

The AFD, BAG, and ASE Sensory Neurons Exhibit Distinct CO₂ Responses

C. elegans, like mammals, monitors CO₂ using multiple neuron types. CO₂ sensors include the ASE neurons with sensory endings directly exposed to the external environment and AFD and BAG neurons whose dendrites lie within the animal. All three neuron types are primary CO₂ sensors: their CO₂ responses are unimpaired in unc-13 mutants defective in synaptic release. Each neuron type has a unique CO₂ response. In AFD, a rise in CO₂ triggers an initial drop in intracellular Ca²⁺ levels (AFD ON-minimum), then a rise above baseline (AFD ON-maximum), and when CO₂ is removed, a spike (AFD OFF-maximum). This complexity may reflect multiple CO₂-transduction mechanisms. In contrast, BAG and ASE neurons are activated by a rise, but not a fall, in CO₂. In BAG, Ca²⁺ peaks within 60 s of a rise in CO₂, then decays to a plateau that persists as long as CO₂ remains high; Ca²⁺ drops back to baseline upon CO₂ removal. AFD responds slowly to CO₂ exposure: Ca²⁺ takes 2 min to peak but remains elevated while CO₂ is high. The tonic activity of BAG and ASE neurons in high CO₂ may allow C. elegans to modify responses to other cues, perhaps by affecting sensory pathways or inter-neuron networks.

AFD, BAG, and ASE also sense other stimuli. AFD senses temperature (Kimura et al., 2004), BAG senses ambient O₂ (Zimmer et al., 2009), and ASE senses salt (Suzuki et al., 2008). This may enable sensory integration within sensory neurons. For each of the three neurons, CO₂ and non-CO₂ stimuli evoke distinct Ca²⁺ responses. When temperature rises above the cultivation level, AFD responds with a monophasic Ca²⁺ spike that lasts a few seconds (Kimura et al., 2004; Clark et al., 2007). The dissimilar CO₂ and temperature responses suggest that the two stimuli are sensed differently. Supporting this, AFD responds to CO₂ below the cultivation temperature. The Ca²⁺ responses of BAG to high CO₂ and low O₂ are more similar in shape (Figure 3) (Zimmer et al., 2009). In contrast, the responses of ASE to CO₂ and NaCl differ markedly (Figure 4) (Suzuki et al., 2008). First, unlike CO₂, NaCl evokes an asymmetric response in ASE and ASER: a rise in NaCl triggers a Ca²⁺ spike in ASE but a drop in Ca²⁺ in ASER. Second, ASEL/R Ca²⁺ responses to NaCl adapt rapidly, whereas sustained CO₂ stimulation leads to sustained high Ca²⁺ in ASE (Figure 4F). Third, whereas ASE responses to CO₂ are slow, taking around 2 min for Ca²⁺ to peak, responses to NaCl peak within 30 s of stimulus exposure. The slowness of ASE CO₂ responses could reflect rate-limiting hydration of environmental CO₂.

**cGMP Signaling Mediates CO₂ Responses**

CO₂ sensing in AFD, BAG, and ASE involves cGMP signaling. Mutating the cGMP-gated channel subunit tax-2 partially abolishes the AFD Ca²⁺ response to CO₂ and completely abolishes CO₂-evoked activity in BAG (Figure 5). CO₂-evoked Ca²⁺ responses in ASE likely also depend on cGMP-gated channels because expression of tax-2 cDNA in ASE in tax-2 mutants partially restores CO₂ avoidance (Figure 1). In mouse olfactory epithelia, CO₂ sensing requires the transmembrane guanylate cyclase GC-D, which is activated by HCO₃⁻ (Hu et al., 2007; Zimmer et al., 2009).
The hallmarks that make GC-D HCO$_3^-$ regulated are unknown, but the C. elegans genome encodes 27 transmembrane guanylate cyclase (gcy), a subset of which could be similarly regulated (Yu et al., 1997; Ortiz et al., 2006). The AFD neurons express gcy-8, gcy-18, gcy-23, and gcy-29. gcy-8 gcy-18 gcy-23 triple mutants have a thermotaxis defect similar to that of the AFD specification mutant ttx-1 (Inada et al., 2006), but have no defect in CO$_2$ avoidance in a 5%-0% CO$_2$ gradient (data not shown). ASE neurons express 11 transmembrane guanylate cyclases, nine of which are expressed asymmetrically either in ASEL or ASER (Ortiz et al., 2006).

Transmembrane guanylate cyclase expression has not been reported in BAG. However, BAG expresses the atypical soluble guanylate cyclases GCY-31 and GCY-33 (Yu et al., 1997). Simultaneously disrupting gcy-31 and gcy-33 reduced the CO$_2$-evoked Ca$^{2+}$ response amplitudes in BAG, suggesting that GCY-31 and/or GCY-33 contribute to CO$_2$ sensing. GCY-31 and GCY-33 are thought to function as heterodimers that have an O$_2$-binding heme cofactor (Boon and Marletta, 2005) and are required for BAG O$_2$-evoked Ca$^{2+}$ responses when O$_2$ drops below 10% (Zimmer et al., 2009). An intriguing possibility is that the GCY-31/GCY-33 heterodimer is inhibited by O$_2$ and activated by CO$_2$, making it a sensory integrator of CO$_2$ and O$_2$ signals in BAG (Figure 8A); however, we cannot rule out the possibility of a linked mutation disrupting BAG responses.

AFD, BAG, and ASE are unlikely to be the only CO$_2$-responsive neurons in C. elegans. The AQR, PQR, and URX O$_2$-sensing neurons showed sporadic responses to CO$_2$ (Figure S2), and selective expression of tax-2 cDNA in these neurons partially restored CO$_2$ avoidance to tax-2(p694) mutants, suggesting that they are CO$_2$ sensitive. Moreover, more than ten C. elegans neurons express carbonic anhydrases, some of which may be unidentified CO$_2$ sensors.

### The Contribution of Different Sensors to CO$_2$ Avoidance Varies with Stimulus Dynamics and Context

Why does C. elegans have multiple CO$_2$ sensors? One reason is that sensors are deployed differently according to the dynamics of the CO$_2$ stimulus. For example, when food is absent, BAG mediates responses to sharp CO$_2$ gradients but is less important for navigating shallow gradients (compare Figures 5G and 6B). A second reason is that context modifies the behavioral changes needed to escape CO$_2$. For example, when food is present, C. elegans move slowly and reverse frequently. To efficiently escape high CO$_2$ in a food-containing environment, C. elegans increase speed and suppress reversals relative to the "on food" ground state. By contrast when food is absent, animals are already moving quickly and reversing less frequently. Correspondingly, the importance of BAG for CO$_2$ avoidance depends on both stimulus shape and food context. Whereas BAG-ablated animals respond poorly to rapid CO$_2$ changes when food is absent, they respond like wild-type animals when food is present (pBAG::egl-1, Figures 6 and S6). Conversely, in shallow gradients BAG acts redundantly with AFD to promote CO$_2$ avoidance when food is present but is not important when food is absent, even when AFD is ablated (Figure 5G).

How do the Ca$^{2+}$ responses of CO$_2$ sensory neurons encode behavior? CO$_2$-evoked neuronal events in AFD and BAG correlate with peaks and troughs in locomotory rates (Figure 6A). To investigate these relationships, we ablated CO$_2$ sensors. One caveat of neuronal ablation is that it can only remove a neuron in its entirety, and not individual components of its responses. Ablation of AFD and BAG neurons one at a time and together suggests that: (1) BAG activation and the AFD ON-minimum act antagonistically, promoting and suppressing reversal and omega rates, respectively (Figures 7C and 7I); (2) BAG plateau activity and the AFD ON-maximum both act to promote reversal and omega rates during maintained high CO$_2$ (ttx-1; BAG(-), Figures 7E and 7K); and (3) decay of BAG activity and the AFD OFF-maximum act together to suppress reversals and omega turns following CO$_2$ removal (ttx-1; BAG(-), Figures 7F and 7L). Together our data suggest that when an animal is migrating up a CO$_2$ gradient, BAG and AFD trigger turning, whereas when...
CO₂ Avoidance Behavior in C. elegans Appears to Be a Homeostatic Mechanism

Elevated tissue CO₂ is toxic (Richerson, 2004). In C. elegans, CO₂ levels exceeding 9% disrupt body muscle organization and general development and reduce fertility (Sharabi et al., 2009). The CO₂ responses of AFD, BAG, and ASE neurons do not habituate upon multiple exposures to CO₂ (Figures 2 and 3; data not shown). C. elegans CO₂ avoidance in spatial gradients is also nonhabituation over a similar period (data not shown). By contrast, C. elegans attraction to benzaldehyde (L’Etoile et al., 2002), response to noxious Cu²⁺ ion stimuli (Hilliard et al., 2005), and response to noise touch (Kindt et al., 2007) all habituate. Moreover, BAG and ASE neurons show tonic signaling while CO₂ levels are high, at least over 20 min. We speculate that C. elegans CO₂ avoidance habituates slowly and performs a homeostatic function by preventing CO₂ poisoning of body tissues. C. elegans CO₂ avoidance provides an opportunity for detailed examination of a CO₂ homeostatic system with comparative ease relative to the systems of more complex animals.

EXPERIMENTAL PROCEDURES

Strains

Strains were grown at 22°C under standard conditions (Brenner, 1974). Mutant combinations were made by following visible phenotypes or using PCR to confirm genotype. A full list of strains can be found in Supplemental Experimental Procedures.

Behavioral Assays

Spatial CO₂ gradient assays were as described (Bretscher et al., 2008). Briefly, polydimethylsiloxane (PDMS) chambers connected to gas syringe pumps were placed over adult worms on a 9 cm agar plate. After 10 min the distribution of worms was used to calculate a chemotaxis index (Figure 1). Chemotaxis bar graphs represent the average of nine independent assays performed over 3 days.

For temporal gradient assays a square 11 × 11 x 0.2 mm PDMS chamber was placed over adult worms on 6 cm agar plates. For off-food assays, ~40 animals were picked after washing in M9 Buffer to remove adhering E. coli. For on-food assays, a 2-day-old 20 µl E. coli lawn was used. Worms were allowed to crawl on food for 1 hr. After placing the chamber, animals were left for 4 min before exposure to a 0%-5%-0% CO₂ stimulus. Behavior was captured using a Grasshopper CCD camera (Point Grey Research). A TTL-output from a frame counter (custom built) controlled opening and closing of TeflonTM pinch valves (Automate Scientific) at defined time points, controlling the switching of gases. Worms were tracked using DIAS Software (Solltech), and worm object valves (Automate Scientific) at defined time points, controlling the switching of a frame counter (custom built) controlled opening and closing of TeflonTM using a Grasshopper CCD camera (Point Grey Research). A TTL-output from 3; data not shown).

CO₂ Avoidance in spatial gradients was also nonhabituating over a similar period (data not shown). By contrast, C. elegans attraction to benzaldehyde (L’Etoile et al., 2002), response to noxious Cu²⁺ ion stimuli (Hilliard et al., 2005), and response to noise touch (Kindt et al., 2007) all habituate. Moreover, BAG and ASE neurons show tonic signaling while CO₂ levels are high, at least over 20 min. We speculate that C. elegans CO₂ avoidance habituates slowly and performs a homeostatic function by preventing CO₂ poisoning of body tissues. C. elegans CO₂ avoidance provides an opportunity for detailed examination of a CO₂ homeostatic system with comparative ease relative to the systems of more complex animals.

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In all experiments, percent (%) CO₂ was balanced by percent (%) N₂ while 21% O₂ was maintained. In rescue experiments, transgenic animals were pre-selected by following coinjection markers. In all figures, statistical significance was determined using the two-tailed Student’s t test.

Calcium Imaging

Ca²⁺ imaging was on an inverted microscope (Axiovert; Zeiss), using a 40x C-Apochromat lens and MetaMorph acquisition software (Molecular Devices). Agarose pads were made in M9 Buffer (pH 6.8) and 1 mM CaCl₂, mimicking an NGM substrate. Worms expressing the Ca²⁺ sensor YC3.60 showed wild-type avoidance in 5%-0% CO₂ gradients (Figure S1). Worms were glued to pads using Nexceland glue (WPI Inc.) and placed under the stem of the Y-chamber microfluidic device. Photobleaching was minimized using a 2.0 optical density filter and a shutter to limit exposure time to 100 ms per frame. An excitation filter (Chroma) restricted illumination to the cyan channel. A beam splitter (Optical Insights) was used to separate the cyan and yellow emission light. The ratio of the background-subtracted fluorescence in the YFP and CFP channels was calculated with Jmalyze (Kerr and Scharfa, 2008). Fluorescence ratio (YFP/CFP) plots were made in MATLAB. Movies were captured at 2 fps. Average Ca²⁺ traces were compiled from at least six recordings made on 2 or more days.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, six figures, one table, and two movies and can be found with this article online at doi:10.1016/j.neuron.2011.02.023.

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