1. Introduction
2. How an Animal Senses Its Environment
   1. Extracellular fluid allows internal cells to communicate with the external environment; membranes allow exchange between extracellular and intracellular fluids
   2. Molecule binds to receptor, triggers pathway cascade leading to physiological change. Will involve up- and down-regulation of genes, changes in concentrations of hormones, ions, etc.
   3. Signal transduction: paracrine, neurotransmitter, hormones, neurohormone, pheromones, cytokines
   4. Types of signaling molecules: eicosanoids, gases, purines, amines, peptides, steroids
   5. Referenced negative feedback: sensor, integrator, and effector. 2 types of effector are antagonistic control or behavior.
3. General Homeostasis in the Oyster – How is it Maintained?: sensory and response
   1. Oysters are conformers
   2. The Bivalve nervous system (Barnes)
      1. Bilateral NS with 3 pair of ganglia and 2 pairs of long nerve cords
      2. Cerebropleural ganglia are on either side of the esophagus and attached to a nerve cord that goes up through the viscer and terminates in the visceral ganglia on the adductor
      3. The second pair of nerve cords go to the pedal ganglia and the 3rd ganglia is cerebral
      4. On many species the mantle edge has pallial tentacles with tactile and chemoreceptor cells
      5. Statocysts in the foot or within the pedal ganglia and innervated by the cerebral ganglion, but reduced in attached oysters
      6. Ocelli along the mantle or on siphons are mostly just pigment spots but in more advanced have cornea and lens
      7. Osphradium beneath the posterior adductor achieve chemoreception of the water in the mantle cavity
   3. Mobile immune-brain and juxtaganglionar organ – scattered cells in connective tissue around cerebral ganglion, release of signaling molecule (?)
   4. Molluscan veligers, as explored in the gastrodpod *Philine aperta*, have serotonergic neurons that connect to the ciliary band (Hay-Schmidt 2000)
   5. Opiate receptor in *M. edulis* pedal ganglia – upreg +IL-1 (modulate proinflammatory events), downreg +morphine (feedback mechanism) (Cadet & Stefano 1999)
   6. Surf clam *Spisula solidissima* has multiple photoreceptive pigments that stimulate pallial nerve in both excitatory and inhibitory ways; evidence for mediation of different responses to shadowing and illumination (Kennedy 1960)
   7. *C. gigas* releases noradrenaline and dopamine (its precursor) in response to mechanical stress in concentrations proportional to intensity and duration of stressor(Lacoste et al. 2001a)
      1. T and salinity elicit long-lasting catechomalime increases (2001a)
      2. Clusters of cells around heart probably release both (2001b)
      3. Release of catecholamines mediated by neuropeptide ACTH (2001b)
   8. Oyster larvae (*Crassostrea* spp.), hypothesized pathway: environmental cues stimulate dopaminergic pathway through epithelial receptors -> increase larval sensory input to environmental factors -> find suitable habitat and stimulate catecholamines and adrenergic pathway to metamorphose (Bonar et al. 1990)
4. Changes Due to OA that Would Affect an Oyster
   1. Dissolved CO2 will more readily diffuse across animal surfaces and reach equilibrium intra- and extracellularly (Fabry et al. 2008)
   2. CO2 reacts with internal fluids, decreasing pH with limited physiological counteraction: passive buffering if ECF and ICF; ion exchange and transport; CO2 transport on respiratory pigments; metabolic suppression (Fabry et al. 2008)
   3. pH of 7.8 and 7.6, Sydney rock oyster larvae have pitted and deformed shell deposition from problems with deposition, retarded periostracum formation, and increased shell dissolution (Watson et al. 2009)
   4. 380 ppm (8.2) vs 3500 ppm (7.5) (Beniash et al. 2010)
      1. juveniles after 20 weeks: increased mortality, decreased dry shell mass and soft tissue mass, decreased fracture toughness, thicker calcitic laths, 2x standard metabolic rate – higher cost of basal metabolism, reduced shell growth from less available CaCO3 and overall decrease in somatic growth
      2. adults after 2 weeks: carbonic anhydrase expressed more in mantle than gills (converts CO2 into bicarbonate for mineralization)
5. Maintaining Internal pH
   1. Preliminary data show that even though osmo- and thermoconformers, may not be as much pH conformers
   2. Buffering accomplished mostly by HCO3- and other buffers and is more efficient intracellularly than extracellularly. Intracellular compartments are already 0.5-0.8 more acidic (Portner et al. 2004)
   3. Marine invertebrate membrane proteins involved in pHi homeostasis: v-type H+-ATPase, Na/H- and Na-dependent Cl/HCO3 exchange (Portner et al. 2004)
   4. At low pH (7.5 vs. 7.9) in body wall musculature of *Spinculus nudus* recovery of pHi was longer and delayed onset of recovery. (Portner et al. 2000)
      1. Regulation of pH recovery mediated by Na/K-ATPase, Na/H exachanger, H+-ATPase, Na-dependent Cl/HCO3 anion exchanger
      2. Recovery rate was slow compared to vertebrates
      3. Low pHe (7.5) caused reduced H+ exchange and reduced flexibility to respond
      4. Accumulation of HCO3 may be precondition for recovery of pHi during hypercapnic acidosis
      5. Differential use of transporters during acidosis causes increased ATP demand – cost is offset by metabolic depression
   5. Membrane carriers transport H+ and/or HCO3 to accumulate HCO3 and compensate pH drop (Portner et al. 2004)
   6. *C. gigas* exposed to pH 7.68 over 55 days: increased extracellular pCO2, decreased hemolymph pH ~0.5 units, increased [HCO3], changes in [Na], [K], and [Ca], decreased pO2, decreased body condition index. Alanine and ATP in mantle decreased from stimulated gluconeogenesis because OA inhibits glycolysis. Increased succinate in gills and hepatopancrease from anaerobic metabolism. pHe affects metabolic rate proportionally (Lannig et al. 2010)
   7. *M. edulis* degraded proteins to increase HCO3 for pHi regulation at low pH over 8 weeks. (Thomsen & Melzner 2010)
   8. Clam *Laternula elliptica* at pH 7.78 over 120 days increased O2 consumption and had elevated Hsp70 in mantle and increased basal metabolic rate (Cummings et al. 2010)
   9. *M. edulis* adults exposed to pH 7.4 for 3 months: slower shell growth, pHe dropped ~0.2 units within 2 days and stayed low, increase in hemolymph pCO2 within 4 days; linear increase in [HCO3]e and [Ca] in first 4 days then steady (Michaelidis et al. 2005)
      1. Preliminary respiratory acidosis then compensation by accumulation of HCO3 to prevent further pHe decrease
   10. Elevated sensitivity of marine invertebrates may be because low capacity to acid-base regulate pHe – hypometabolic, not enough resources (Portner et al. 2008)
6. Impacts on Immune Function
   1. Hemolymph changes pH and that is basis of immune function
   2. In *M. edulis*, decreased pH (6.5, 7.6, 7.8) for 60 days caused leaky lysosomes. Could lead to increased permeability to substrates, activation of cell death, disruption of normal lysosomal function, cytolytic damage, and effects on immunity (phagocytosis, endocytosis, autophagy) (Beesley et al. 2008)
      1. Lysosomal enzymes are associated with hemolymph: acid phosphatase, lipase, aminopeptidase, lysozyme. Are released during phagocytosis (Cheng in TEO)
   3. Mussel 32 day exposure to elevated CO2 7.8, 7.7, 7.5, 6.7: decreased phagocytosis (days 16 & 32)(Bibby et al. 2008)
      1. Surmise that caused by increased levels of Ca (not measured directly, but shells more brittle); important signaling molecule for hemocytes
   4. Hemoctye migration is temperature dependent; salinity affect granulocyte movement (Cheng in TEO)
   5. Greater infection in *C. virginica* after exposure to TBT and hypoxia (Anderson et al. 1998)
   6. Mussel exposure to copper then Vt: fewer hemocytes at lower T (10C) and at high Cu (0.05 ppm), increased phagocytosis by increasing T to 15C, phagocytosis increased with low Cu or Vt and then decreased at higher levels of both (Parry & Pipe 2004)
   7. Cu + Vt for mussels: low Cu number of circulating hemocytes decreased could be migrating to tissues; at high Cu hemocytes increased; at 15C increase of SOD inhibitable superoxide production (Parry & Pipe 2004)
   8. Salinity (15 ppt) and temperature (25C) stress initially decrease hemocyte phagocytic activity *in vitro* using a proxy for foreign particles in *O. edulis*. Acclimation occurs by 24h and is maintained, at least for T, up to 72h. (Fisher et al. 1987)
7. Conclusion
   1. Compensation for a preliminary stress may come at a cost to another physiological process