

BIOLOGICALLY-INSPIRED CONTROL OF PERCEPTION-ACTION SYSTEMS: HELICAL KLINOTAXIS IN 2D ROBOTS

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Abstract

Some animals that swim at low- ($Re < 1$) and intermediate- ($1 < Re < 100$) Reynolds numbers do so by way of helical trajectories. Movement towards or away from stimuli involves the detection of gradients, alteration of the helical trajectory, and subsequent gradient tracking and steering by the animal. Using sensory and neural circuitry models from simulations of swimming sea squirt larvae (Phylum Chordata, Subphylum Urochordata), we have built and tested a one-eyed, tail-flapping robot that swims up a light gradient and holds station at a particular intensity. By so doing we have (1) tested and supported one of the neural circuitry models proposed in the simulations of Strother and McHenry (2002), (2) shown the simplicity and effectiveness of using a single light sensor for navigation, and (3) investigated the use of helical motion in two dimensions.

Introduction

Our goal is to adapt a biological principle for implementation in an aquatic robot. We use the principle of one-eyed or cycloptic helical klinotaxis (cHK) – a simple and robust form of gradient detection and navigation in 3D

(Kemp, 2001; Kemp et al. 2001) – used in the swimming tadpole larvae (~ 3 mm total length; Fig. 1) of sea squirts (Phylum Chordata, Subphylum Urochordata, Class Ascidea) in order to orient towards and away from light ('phototaxis') at low and intermediate Reynolds numbers ($Re < 100$). By implementing cHK in robotic systems constrained to 2D motion, we address several questions. (1) Is a single sensor sufficient for directional navigation? (2) Is a single control variable, rotational velocity ω , sufficient for control of 2D HK? These two issues, under the general heading of 'perception and action,' are functionally linked by the shared use of a control circuit situated in a common vehicle (Chiel & Beer, 1997).

In a computer simulation of swimming sea squirt tadpoles, Strother and McHenry (2002) tested four neural circuitry models posited to control cHK. Each circuit linked the tadpole's single photosensitive eyespot ('ocellus') to muscles that bias the undulatory

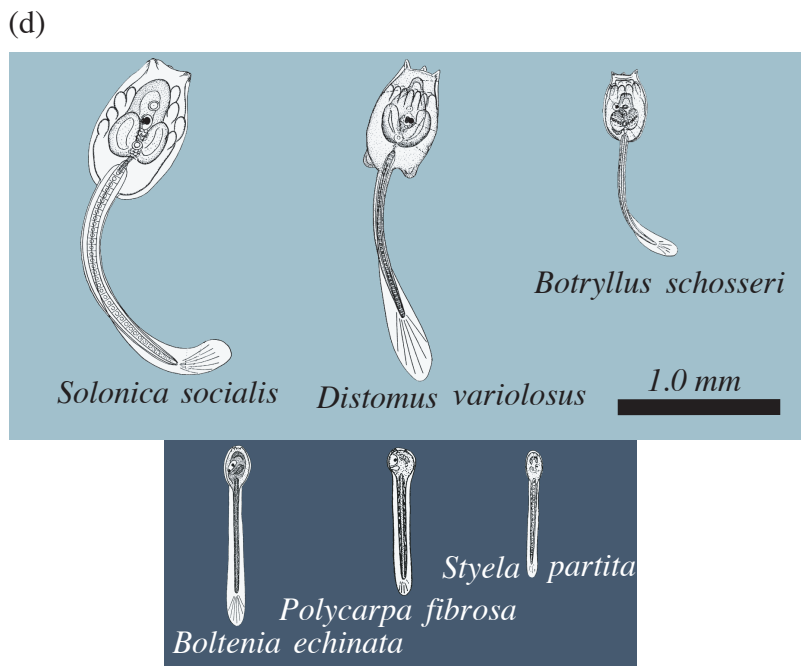
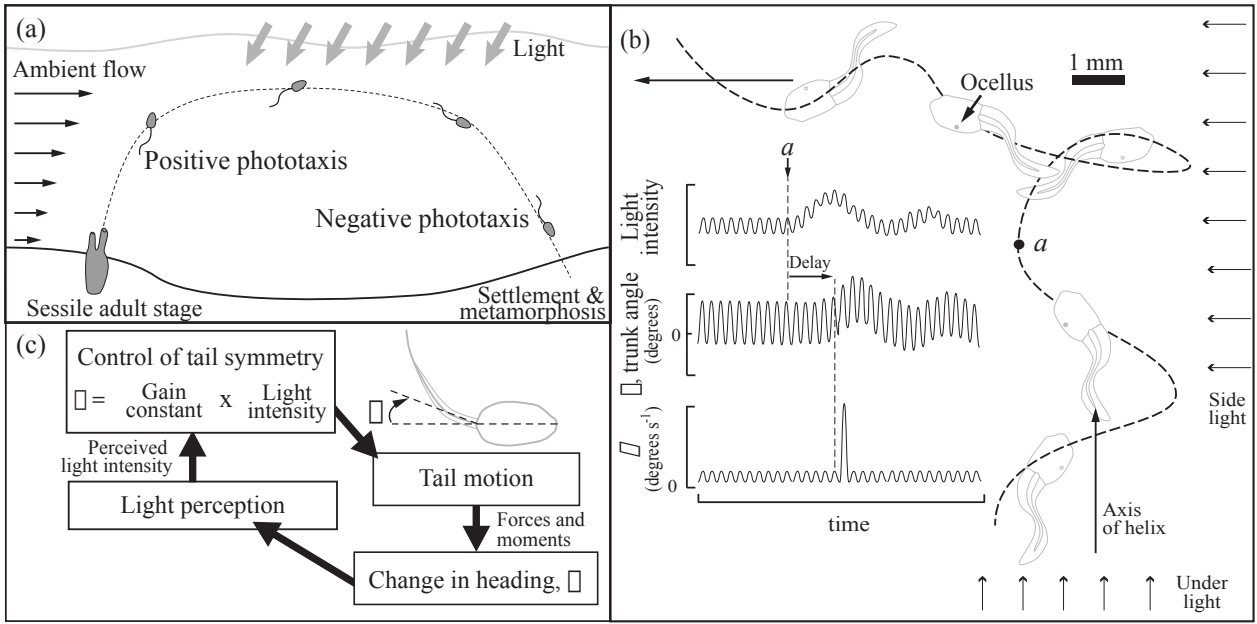


Figure 1. Phototaxis in ascidian larvae. (a) Upon release from the adult stage, an ascidian larva uses positive phototaxis to swim into the water column, where larvae are carried by ambient flow. Later in the dispersal stage, larvae use negative phototaxis to find a settlement site on the substrate. (b) The kinematic mechanism of phototaxis proposed by McHenry & Strother (2003), suggests that an experimental change in the direction of illumination (from "Under" to "Side" light at "a") causes a slow oscillation in perceived light intensity, which triggers an asymmetry in tail beating (non-zero mean \square) that triggers a change in heading, \square , that in turn alters the orientation of the body and direction of the axis of the helical trajectory. (c) The asymmetry of tail beating, \square , is hypothesized to be proportional to perceived light intensity. This asymmetry generates forces and moments that cause the body to change its heading, \square , which changes the perceived intensity of light, altering the \square signal. (d) Range of sizes and larval body morphologies in colonial (top panel) and solitary (bottom panel) species.

tail motion to the right or the left. The simplest circuit that produces realistic phototactic behavior changes the tail's bias angle, θ , in proportion to the intensity of light sampled by the ocellus. The θ asymmetry, in turn, controls the curvature of the animal's path, given a constant translational velocity, by varying rotational velocity, ω . Over time, the curved path allows the single sensor to behave as a directional photoreceptor (Crenshaw, 1996). This is the circuit that we used in a robot of an ascidian larva.

We implemented this model in a surface-swimming robot using an analog electronic circuit, which is a modified window comparator with an effective window of zero. This narrow window couples light intensity at the photoresistor to a motorized potentiometer that alters the θ orientation of the propulsive flapper. The difference between resistances at the sensor and the potentiometer is minimized; thus, the system operates using negative feedback between the external light sensor and the internal motor position sensor.

We also implemented 2D cHK on a terrestrial robot. We did so for three reasons: (1) as an independent proof of the 2D cHK principle, (2) as proof of the principle's generality as a perception-action control system, and (3) as an implementation in a digital rather than analog circuit.

Background

Like many marine invertebrate larvae (Young 1995), ascidians can orient their motion towards light in 3D despite having only a single photoreceptive ocellus and a single propulsive appendage. Ascidians are thus unique among larval chordates in that they do not make use of paired sensory organs and fins to orient to sensory cues (Fig. 1).

McHenry and Strother (2003) found that by rapidly changing yaw rate and roll rate, ascidian larvae redirected their swimming away from illumination by varying the θ asymmetry in proportion to the changes in perceived light intensity resulting from body rotation (Fig. 1). During 3D helical motion, an animal spirals as though it were moving on the threads of a screw (Crenshaw, 1996). When a stimulus gradient or vector cue is detected, the axis of the helical trajectory can be changed by altering the animal's θ such that it is oriented in the desired direction of navigation (Crenshaw, 1993a, 1993b). This navigation and orientation to a gradient is 3D helical klinotaxis, where 'klinotaxis' refers strictly to orientation by use of vector information (Frankel & Gunn, 1940). The counter-intuitive result is this — directional control arises from modulation of rotation rather than translation (Crenshaw, 1989, 1990). Thus 3D HK offers a simple, 1 DOF control of complex orientation behavior.

Ground-breaking work in the use of 3D HK for the control of micro-AUVs has been accomplished by Nekton Research (Durham, NC, USA). A working platform, Microhunter™, operates with a single propeller (Kemp et al. 2001) that adjusts trajectory by modulating propeller speed alone (Kemp, 2001). The patented technology for 3D orientation using HK (US patent #6,378,801; 30 April 2002; inventors Pell, Crenshaw, Janet, Kemp; assignee Nekton Technologies, Inc.) relies explicitly on single actuator modulation of both the translational and rotational vectors of the vehicle operating in 3D. Moreover, Kemp (2001) explains how Microhunter fails to operate as predicted by kinematically-based 3D HK theory (Crenshaw 1993a, 1993b, 1996). The system in this paper differs in several respects: (1) it is 2D, (2) it modulates only rotation, (3) it explicitly seeks to operate using kinematic 3D HK theory (Crenshaw

1989, 1993a, 1993b), (4) it includes terrestrial motion, and (5) it uses a biologically-based control scheme derived independently from knowledge of the patent. Even though we began this project before publication of the 3D HK patent, we wish in no way to infringe. We hereby relinquish any claims regarding technological development.

3D HK is used for orientation by a variety of microorganisms, including most ciliated and flagellated unicells (Crenshaw et al. 2000) and by small multicellular animals (McHenry, 2001). 3D HK is widespread in part because it results from any asymmetry in hydrodynamic force generation that induces rotation. In larger animals, such as fish and whales, 3D HK appears to be absent, since fish and whales avoid continuous roll by the use high Re stabilizing forces from fins and flippers. In many situations, such as turning in the lateral plane, rotation is restricted to 2D, and a single rotational axis, yaw, operates. However, tactic orientation in 2D also operates by controlling the body's rotation and may therefore be treated as a special case of HK. Therefore, it may be possible that control systems that facilitate HK in 3D may operate when organisms, or robots, are constrained to 2D.

Successful klinotaxis requires sensing a gradient. Commonly, it is assumed that two sensors are required to make a comparison between two points in a gradient (Braitenberg, 1984, Arkin, 1998, Murphy, 2000). It has been shown, however, that klinotaxis is possible through the use of one sensor if the intensity comparisons are temporal (if the agent is moving, the comparisons will be spatial as well). This system has been established in *E. coli*, *Paramecium*, and the nematode, *C. elegans* (for review Morse et al. 1998). A one-sensor robot successfully modeled the chemotaxis of *C. elegans* using temporal comparisons (Morse et al. 1998).

In contrast, the mechanism proposed by Strother and McHenry (2002) for helical klinotaxis in larvae of *A. constellatum* uses only one sensor and does not make temporal comparisons. Hence, it is less complex, both mechanically and computationally, than other one- and two-sensor methods for orienting to a gradient. This suggests that comparison-style mechanisms have inherent redundancies and that klinotaxis may be implemented in artificial systems in much simpler ways than commonly accepted.

The Cycloptic Aquatic Tadpole Robot

The hull of the robotic tadpole (Fig. 2) was a tapering right-circular, flat-bottomed, plastic container (Rubbermaid, 1.4 l). This shape was chosen as a first approximation of the bulbous anterior section of the ascidian tadpole (see Fig. 1) and to simplify future computer simulations. With ballast, batteries, electronics, and attached stern drive, the displacement of robot was $850 \pm 100 \text{ cm}^2$ (± 1 st. dev.), the length (diameter) at the waterline was 15.8 cm, the draft was 6.2 cm, and the freeboard was 4.8 cm. During experiments, Reynolds number of the robot, using length at the waterline as the characteristic length, ranged from 1580 to 14,200, more than three orders of magnitude above that of actual tadpole larvae, whose hydrodynamics are dominated by skin friction and form force (McHenry et al. 2003).

The movement of the robotic tadpole was controlled by a stern drive with two degrees of freedom (Fig. 2). The propulsive unit was a laterally-oscillating tail driven at a constant frequency, $2.00 \pm 0.04 \text{ Hz}$ (± 1 st. dev.), and amplitude, $5.43 \pm 0.18 \text{ cm}$ (± 1 st. dev.), by a rotary motor (1.5 VDC; single AA battery) attached to a reduction gear box and sliding crank. The lateral oscillation corresponds to the lateral tail motion in an ascidian larva (McHenry 2001). Because of the asymmetry

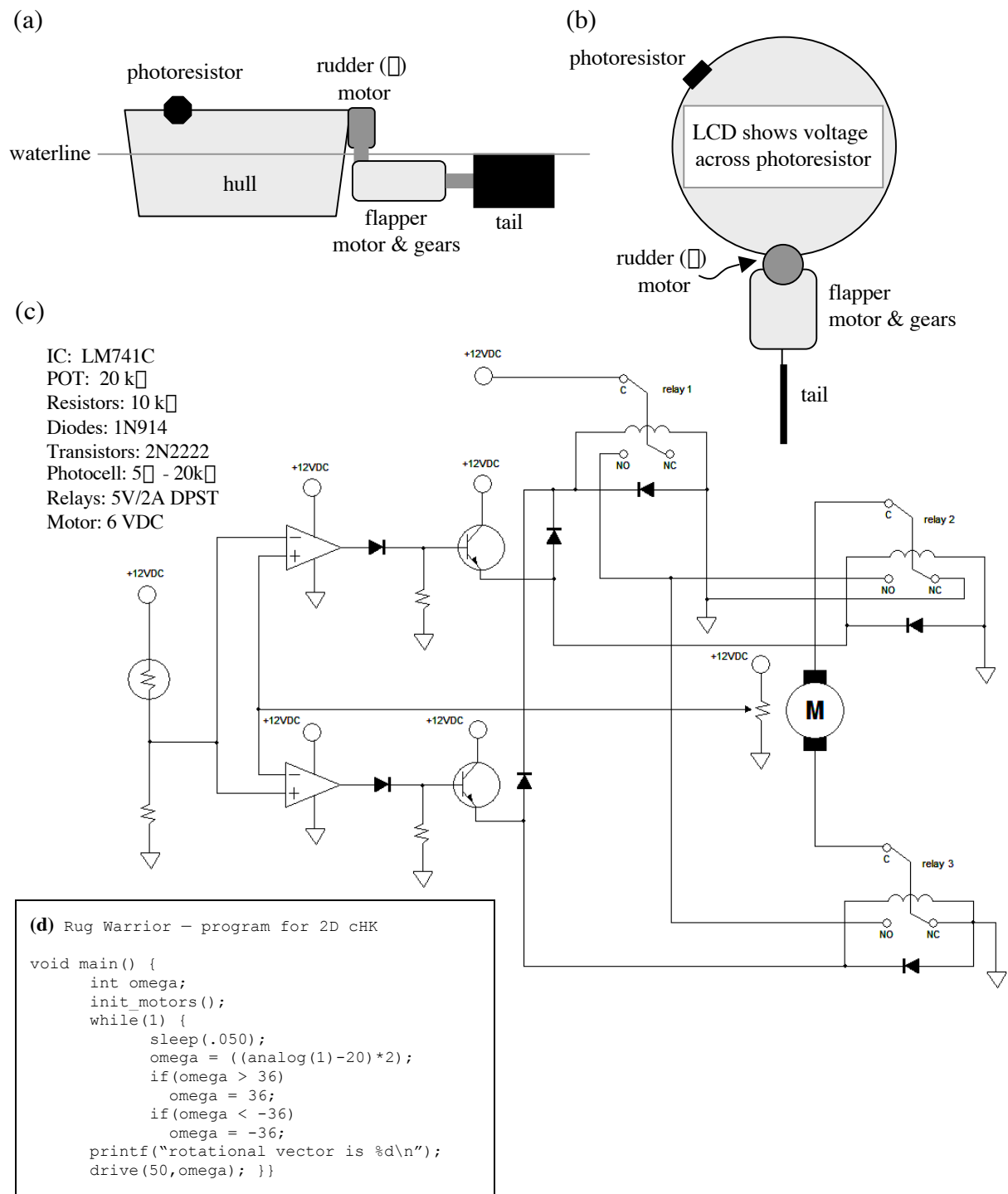


Figure 2. Robotic tadpole and control circuitry. (a) Side view of surface-swimming robotic tadpole. (b) Top view. (c) The analog circuit (window comparator) linking the light intensity sensed at the photoresistor to the position of the rudder motor (M). (d) The complete Interactive C program used to produce 2D cycloptic helical klinotaxis (2D CHK) in the Rug Warrior terrestrial robot. Note that the variable 'omega' is the rotational velocity vector, and is a simple function of 'analog(1),' the voltage across one of the photoresistors.

inherent in this standard design, the resulting tail motion was temporally asymmetric, such that a full lateral motion to one side took slightly longer than to the opposite side. The terminal tail blade was made of duct tape fashioned into a rectangular element of 6.7 cm length x 3.6 cm height x 0.1 cm thickness.

The lateral orientation, θ (in degrees), of the propulsive unit was controlled independently by a separate rudder motor (20 k Ω motorized potentiometer; single 9 VDC battery; Shokai model WHE1604A) attached to the hull and the propulsive drive (Fig. 2). The operation range of θ was approximately $\pm 100^\circ$.

The rudder orientation, ϕ , was controlled by negative feedback in an analog circuit involving input from a photoresistor and output via the rudder motor (Fig. 2). The single photoresistor (20 k Ω) is the sole sensory input, corresponding to the single ocellus of an ascidian larva. The voltage across the built-in potentiometer was used as feedback information for the position of the tail. In the circuit, a pair of operational amplifiers (LM741) act as voltage comparators (Fig. 2). When the voltages from the sensor and the motor are exactly equal, neither comparator produces an output and ϕ remains unchanged. However, when the sensory voltage changes in response to a different light intensity, one of the comparators produces a high voltage output, generating, by way of the relays, a change in the polarity and/or power reaching the rudder motor. Under conditions of changing local light intensity, which depend on the robot's heading and range and bearing to the light, ϕ changed continuously in response to changes. While this type of circuit is called a window comparator, we modified the circuit such that the window is effectively zero and any difference in the voltages caused a response to be triggered.

A digital panel meter (3.5 digit panel meter with liquid crystal display) displayed the voltage across the photoresistor at all points during the trial, in real time.

The Terrestrial Robotic System

We used the Rug Warrior Pro Mobile Robot Kit (A K Peters, Ltd.) because it offers a highly maneuverable differential drive, digital control, and an array of sensors. For our experiments, we disabled all sensors except the left photoresistor, which sits on the same side and at a similar angular orientation on the body as the aquatic robot.

The perception-action loop between sensor and motor output was implemented digitally using the Interactive C programming language. In our simple program, the translational vector was kept constant on any one trial, while the light intensity sensed by the photoresistor was used to alter the rotational vector (Fig. 2). The library functions include one called 'drive()', which takes two arguments, the translational vector and the rotational vector. We coded the translational vector as a constant and the rotational vector as a simple output of a function whose input is the photoresistor voltage. The program also printed the rotational speed on Rug Warrior's liquid crystal display.

Experiments

We created two different light environments for testing the phototactic abilities of the aquatic tadpole robot. In the first, called 'Spotlight', a testing environment was created using a circular tank of diameter 1.82 m that was filled with water to a height of 0.15 m. A light source was positioned 1.00 m above the water level, and 0.21 m inside the rim of the tank. The light was provided by a 125W incandescent spot bulb that was pointed

perpendicular to the water surface. Thus, a light gradient was created, with the point of highest intensity being 10660 lx. This was measured directly under the bulb at the water line, with the light meter tilted 22° from orthogonal to the water's surface while facing the light source. The intensity of light taken similarly on the opposite side of the tank was 144 lx. The decrease in light was characteristically proportional to the inverse square of distance.

The robot was placed in the tank without the spotlight on. After the vehicle rotated three times, we turned on the light. The experiment ceased after the robot had oriented towards the point of maximal intensity, navigated in that direction, and held station around that point for three rotations.

The experiment was repeated three times and recorded using two digital video camcorders, one captured the whole tank (Panasonic model GRL-500) and one following the LCD read out of the voltage across the photoresistor. Digital images were analyzed using motion-analysis software (VideoPoint). We calibrated the photoresistor's voltage to light intensity at its angle and position using a digital photometer (Spectra model Professional IV A). Calibration included values taken as the robot and photometer were rotated and moved at various distances from the light source.

Under these same conditions we repeated the experiments three times with the perception-action circuit off-line. This served as a control for the influence of the stimulus-response system on navigation.

In the second light environment, called 'Threshold,' we divided the tank into halves, both lit with diffuse sources, with one being relatively dark and the relatively light. The light was positioned at a height of 0.80 m above the water's surface, above the rim of

the tank. Unlike the first environment, in which the light was turned on during the experiment, in this case the environment did not change. The experiment began by placing the robot into the dark section facing away from the light side. The experiment ended after the robot had oriented toward the light side, navigated toward that side, and completed three rotations in the light side. The experiment was repeated three times.

It is important to note that that the walls of the tank restricted the motion of the robotic tadpole at times in both sets of experiments. In spite of these occasional interactions, we still had a strong correlation between light intensity and change in the heading of the craft (see Results).

A final set of two experiments was conducted using the Rug Warrior robot under the spotlight conditions. The same protocol was followed as outlined above, except that the trial was not conducted in a tank with walls, and the light source was positioned closer, at 0.71 m above the plane of movement. In the first three trials, the translational vector (adjustable within Interactive C) was set at 35. At this magnitude, the robot pivoted on its right wheel in the dark, station-holding behavior. In the second set of three trials we increased the translational vector by 50%, which changed station holding into a circular path with a larger radius.

Using motion analysis, several points were tracked on the videos, including those corresponding to the front and back ends of the robot. The coordinates were taken with respect to a Cartesian coordinate system with the origin at the center of the tank. The x-axis extended through the light source in the negative direction. Positional information was then used to calculate the heading of the robot with respect to the coordinate system. An orientation parallel to the x-axis and the

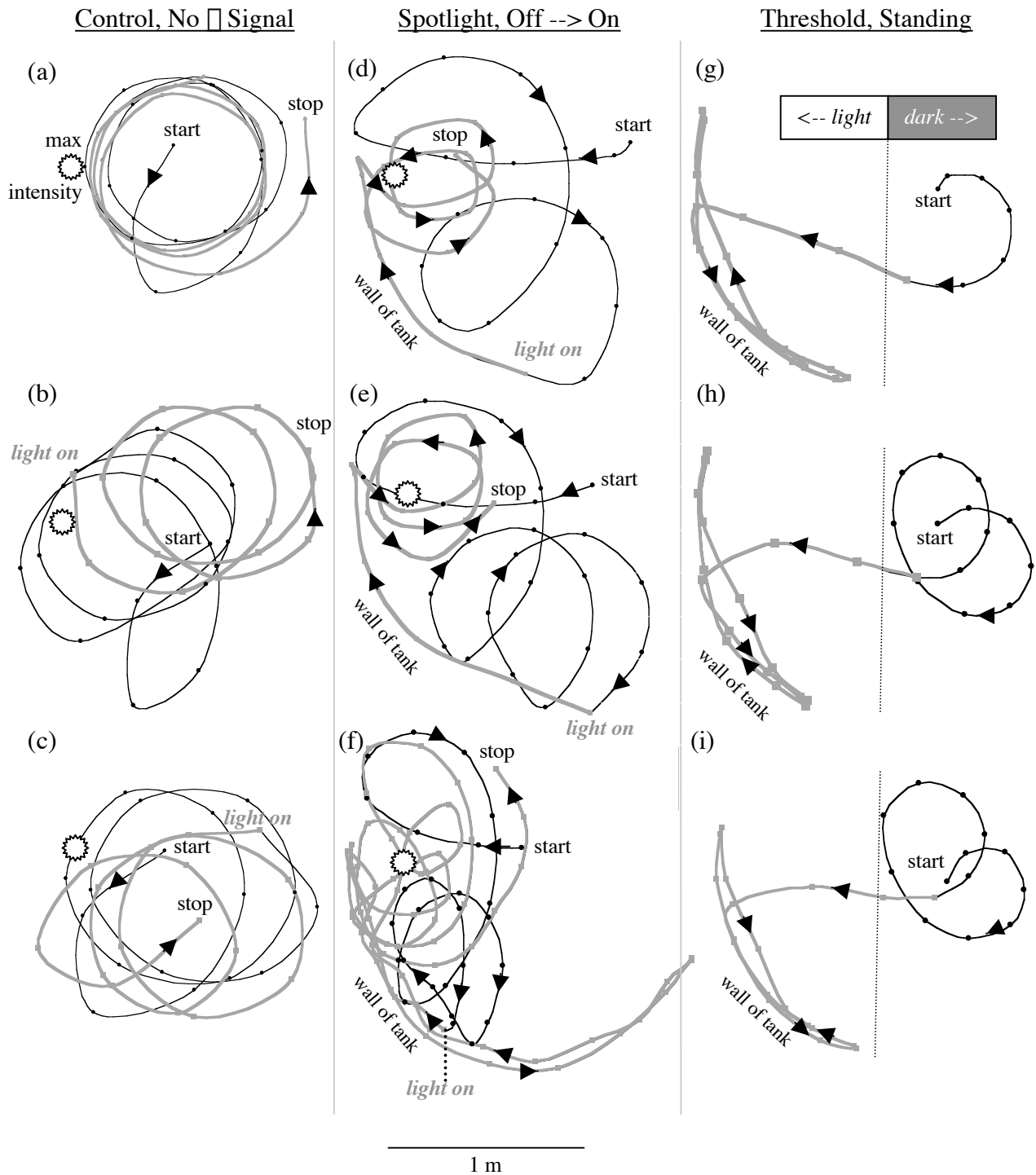


Figure 3. Trajectories of the Robot Tadpole under three different experimental conditions, with start and stop positions indicated. For the control and spotlight experiments, the time when the light was turned on is indicated as the transition point from a black to gray line. In those same experiments, the sun symbol shows the position on the surface of the water of maximal light intensity. In the threshold experiments, the boundary between dark and light conditions is demarcated by the dashed vertical line. The wall of the tank is indicated where the path of the robot is constrained by it. Arrows indicate forward motion.

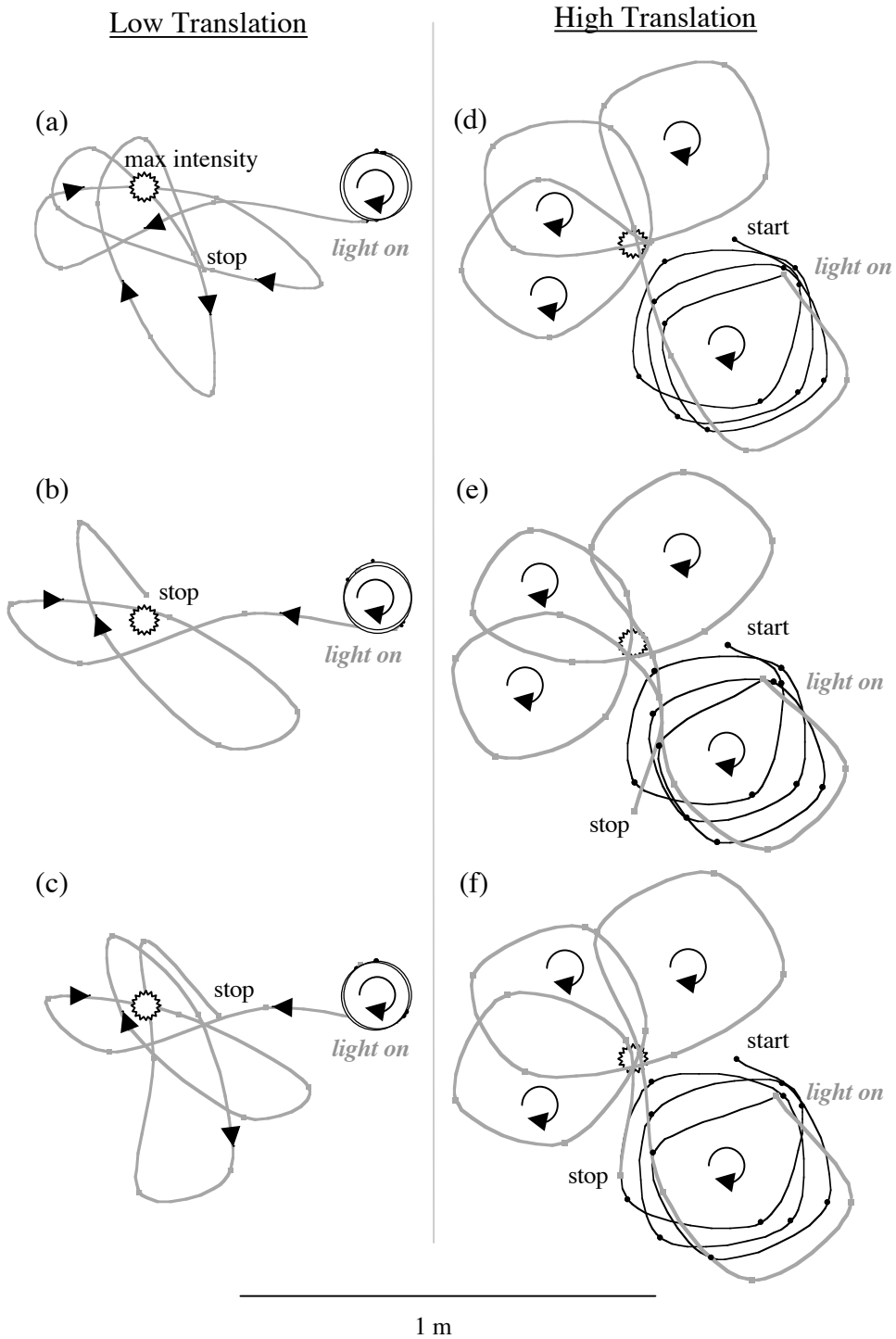


Figure 4. Trajectories of the Rug Warrior under two different experimental conditions, with start and stop positions indicated. The time when the light was turned on is indicated as the transition point from a black to gray line. The sun symbol shows the position on the surface of the floor of maximal light intensity. Arrowheads indicate forward motion, and curved arrows show the direction of rotation for a path section.

front end at a higher x-value was considered a heading of 0° (essentially opposite the light-side of the tank). Also calculated was the difference in heading, $\Delta\theta$, between two temporal points on the video. Finally, the midpoint of the front and back points was calculated to represent the position of the robot within the tank.

Results

The trajectories of the surface-swimming tadpole robot in the control condition (Control column, Fig. 3) were similar before and after the light was turned on. In contrast, once the robot had control of the tail angle (Spotlight and Threshold columns, Fig. 3), the pre-stimulus behavior was quite different from the behavior after the stimulus was introduced. In all cases, the location of the robot was largely near the point of maximum intensity when the light gradient was present. When not in a gradient, the location was much more evenly distributed around the tank. In the spotlight condition, clockwise loops became small-radius counter-clockwise circles after the stimulus was turned on. The location of the tadpole robot in the threshold condition was especially illustrative of this behavioral difference. In these trials, the robotic tadpole performed station-holding until it crossed the light threshold, at which point the robot headed directly for the point of maximum intensity and oscillated around that point.

The Rug Warrior's position in both high- and low-translation conditions (Fig. 4) showed clockwise looping behavior until the stimulus was introduced, which caused Rug Warrior to move toward the light source, and then turn in a series of clockwise loops that passed through the maximum intensity point.

Examination of the heading and the change in heading, $\Delta\theta$, (Fig. 5) quantifies what was qualitatively apparent from the robots'

positional data. For the robotic tadpole, the control experiments showed little difference in the $\Delta\theta$ through any of the trials, whereas the spotlight condition showed a distinct switch in $\Delta\theta$ from negative to positive after the stimulus was turned on. This indicates the change from clockwise to counterclockwise rotation that was observed (see Fig. 3). In the threshold conditions, the heading itself shows how the robot went through 360° rotation once or twice before oscillating around a light-oriented heading. The $\Delta\theta$ for both conditions of the Rug Warrior (Fig. 6) stayed steady until the stimulus was introduced, at which point the heading itself showed a series of straight runs and turn-arounds were apparent.

In the tadpole robot a strong correlation existed between the change in heading, $\Delta\theta$, and the light intensity detected by the photoresistor in the spotlight condition (Fig. 7). All linear regression lines were statistically significant ($p > 0.05$) with coefficients of determination (r^2) greater than 0.63. The Rug Warrior displayed a similar pattern, although the r^2 values were as low as 0.13 and were not significant ($p > 0.05$).

Discussion

From a starting position of low relative light intensity, the aquatic tadpole robot oriented towards greater intensity, moved up the gradient, and held station at or near a preferred intensity (Fig. 3). In two different light environments, the robot's phototactic behavior was controlled solely by modulation of the vehicle's rotational velocity, ω (Fig. 5), a result consistent with predictions from 3D HK theory (Crenshaw, 1993a, 1993b, 1996). Rotational velocity, in turn, was controlled by an analog perception-action circuit that proportionally matched changes in sensed light intensity to changes in the rudder orientation, θ , of the flapping tail (Fig. 7), a

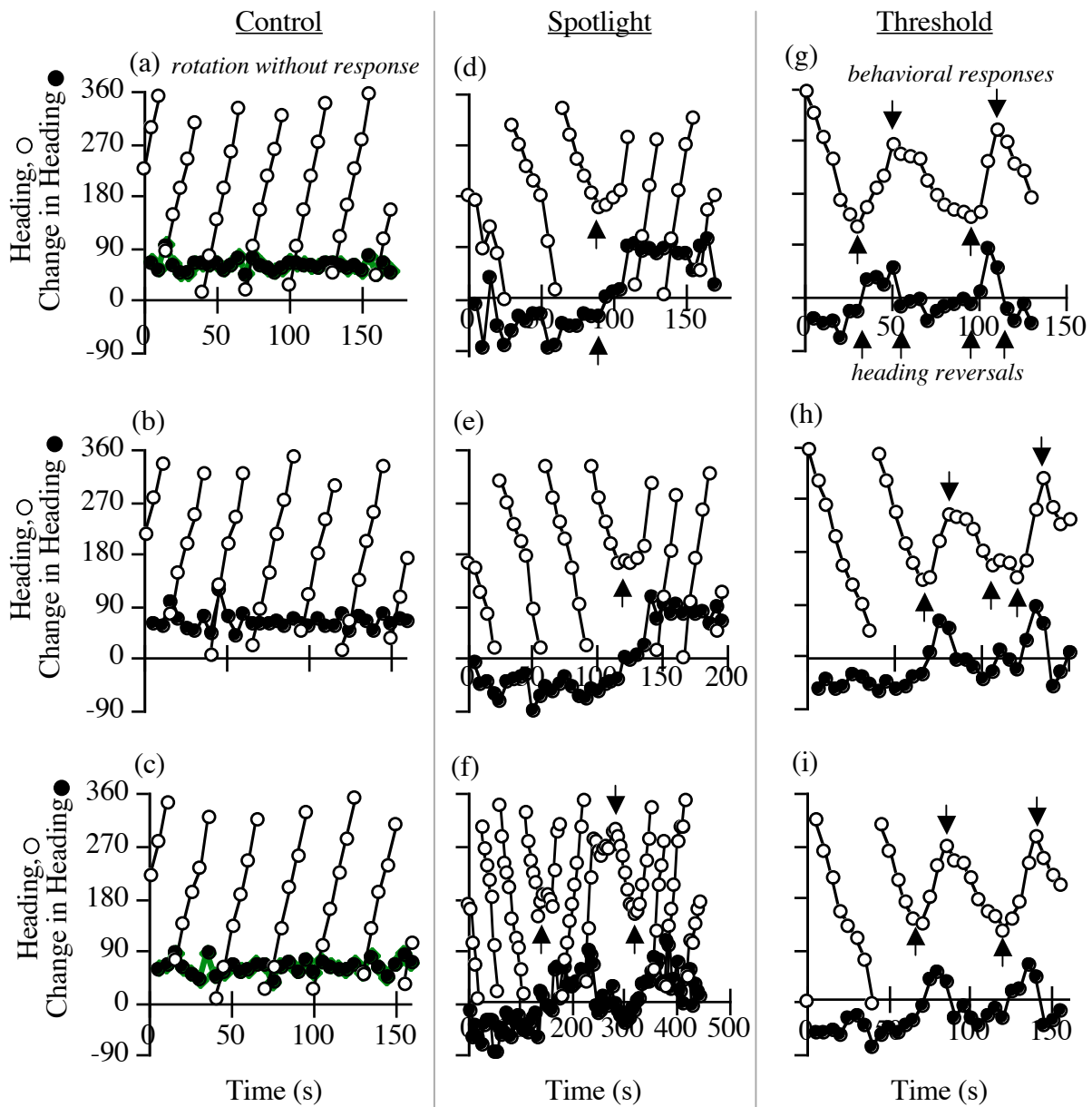


Figure 5. Phototactic responses of Robotic Tadpole as measured by vehicle heading (degrees, open circles) and change in heading (degrees per 5 seconds; filled circles). The control experiments (a-c) are compared to the two different experiments (d-i), with arrows showing the responses as seen in heading and heading reversals. The corresponding change in heading shows a change in the magnitude and/or direction of the rotational velocity vector. The trials correspond to those shown in Figure 3.

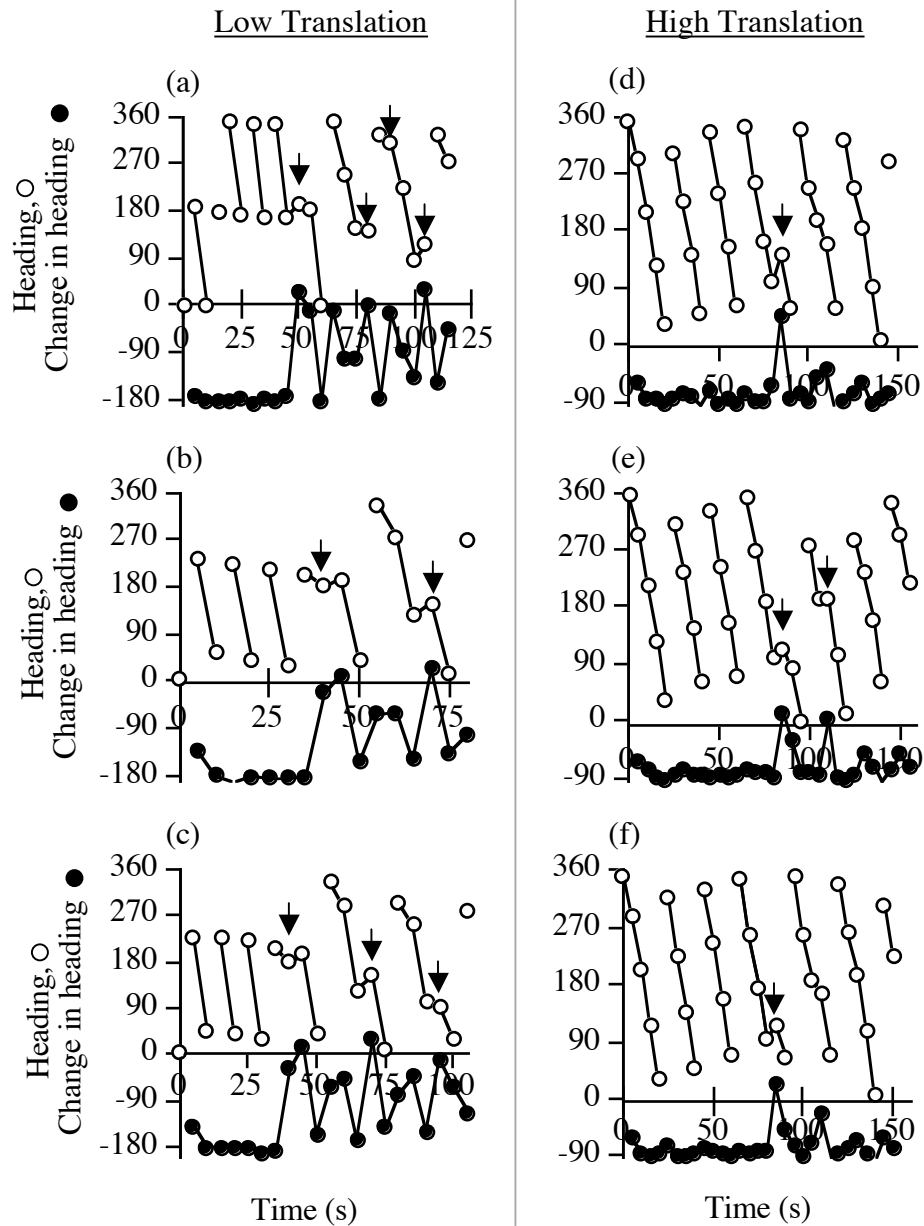


Figure 6. Phototactic responses of Rug Warrior as measured by vehicle heading (degrees, open circles) and change in heading (degrees per 5 seconds; filled circles). Low translation and high translation programs are compared (left and right columns, respectively), with arrows showing the responses as seen in heading. The corresponding change in heading shows a change in the magnitude and/or direction of the rotational velocity vector. The trials correspond to those shown in Figure 4.

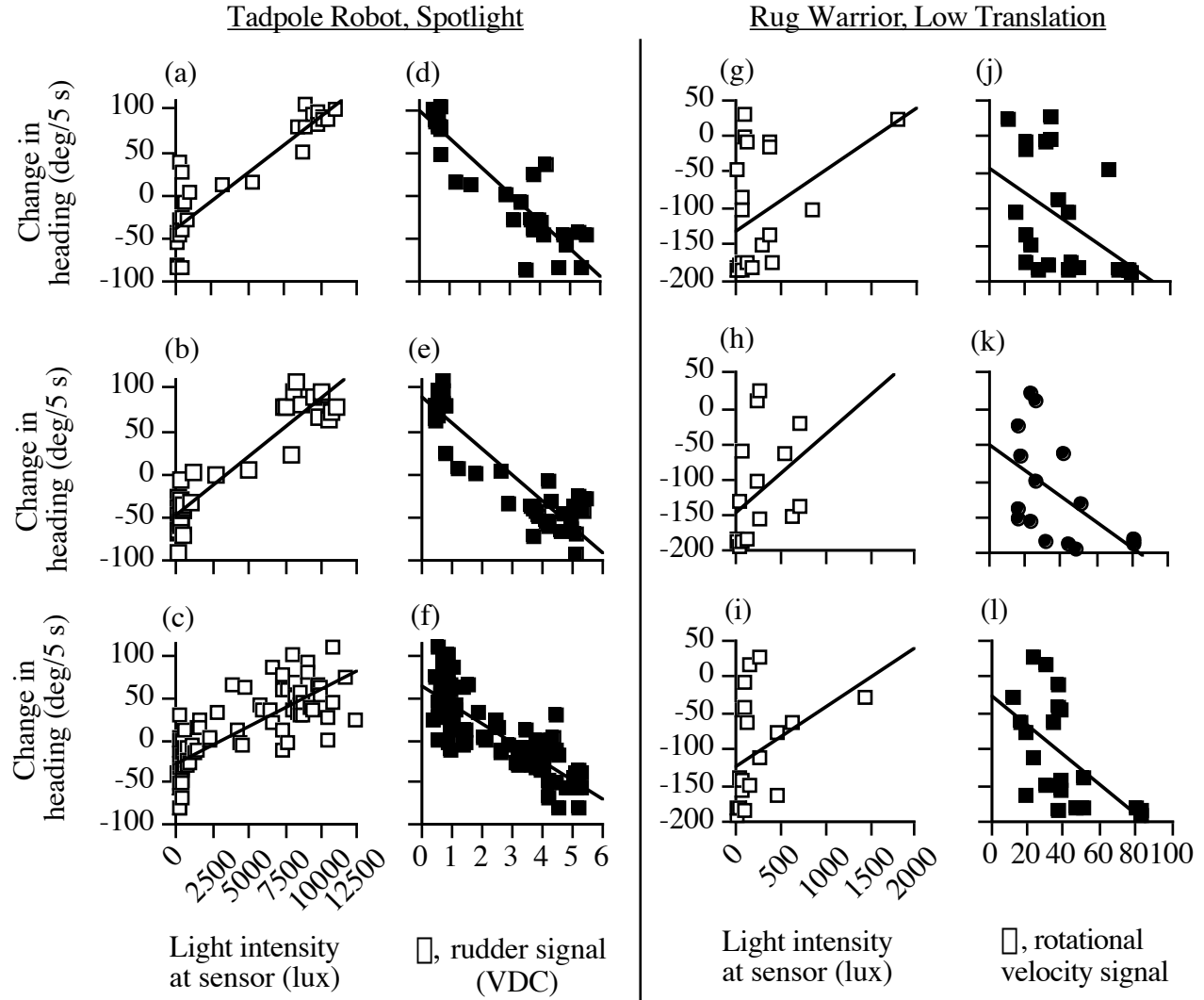


Figure 7. Control of heading change. In the Tadpole Robot (a-f), change in heading is directly proportional to the light intensity detected by the photoresistor. The connection between sensor and behavioral response is mediated by the computed rudder signal, □. Lines are linear regressions (all $p < 0.05$). In the Rug Warrior (g-l), the same general patterns are seen even though the regression lines are not statistically significant in all cases. The pairs of figures in each row and category correspond to the trials shown in Figures 3-6.

result consistent with predictions from computer simulations of ascidian tadpole larvae at low ($Re < 1$) Reynolds numbers (Strother & McHenry, 2002).

For engineers, the most important result of this work is that the simple, single-sensor perception-action control system proposed by Strother and McHenry (2002) works in aquatic robots operating at high Re (>1000) in 2D environments to orient, navigate, and station hold. Cycloptic 2D HK (cHK) is a new navigational mechanism, inspired from biological systems, available for immediate implementation in analog or digital systems. Cycloptic HK has several attractive properties for new or existing platforms:

- (1) single sensor operation — provides redundancy in two-sensor systems, where failure of one sensor could activate cHK to extend mission time or aid in vehicle recovery,
- (2) low control costs — cHK navigation is simple to implement algorithmically, allowing cheap analog or quick computational control,
- (3) vehicle instability tolerance — since cHK acquires gradient information directly from its movement interaction with the environment, platform wobble is subsumed in the continuous perception-action calculation.

For neurobiologists and cognitive scientists, we wish to emphasize that 2D cHK uses only one sensor and does not make temporal comparisons. As demonstrated in both aquatic and terrestrial robotic systems (Fig. 3 & 4), cHK is less complex, both mechanically and computationally, than other one- and two-sensor methods for orienting to a gradient. This suggests that comparison-style mechanisms have inherent redundancies and that klinotaxis can be implemented in natural and artificial systems in much simpler ways than commonly accepted. Moreover, our robotic embodiment of a biological principle, cHK, tests its functionality independently from experiments on the organisms or from computer simulations. Thus, robotic systems

provide another tool for testing biological hypotheses (Webb, 2002). We note that the use of robotic systems for this purpose is the source of much current debate (see Webb, 2001 and the accompanying commentaries).

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