Journal of Computational Neuroscience
https://doi.org/10.1007/s10827-021-00787-4

ORIGINAL ARTICLE

A computational model of the shrimp-goby escape and communication system

Joseph A. Landsittel[1] · **G. Bard Ermentrout**[1] · **Klaus M. Stiefel**[2,3]

Received: 23 May 2020 / Revised: 15 April 2021 / Accepted: 20 April 2021

Abstract
Fish escape from approaching threats via a stereotyped escape behavior. This behavior, and the underlying neural circuit organized around the Mauthner cell command neurons, have both been extensively investigated experimentally, mainly in two laboratory model organisms, the goldfish and the zebrafish. However, fish biodiversity is enormous, a number of variants of the basal escape behavior exist. In marine gobies (a family of small benthic fishes) which share burrows with alpheid shrimp, the escape behavior has likely been partially modified into a tactile communication system which allow the fish to communicate the approach of a predatory fish to the shrimp. In this communication system, the goby responds to intermediate-strength threats with a brief tail-flick which the shrimp senses with its antennae.
We investigated the shrimp goby escape and communication system with computational models. We asked how the circuitry of the basal escape behavior could be modified to produce behavior akin to the shrimp-goby communication system. In a simple model, we found that mutual inhibitions between Mauthner cells can be tuned to produce an oscillatory response to intermediate strength inputs, albeit only in a narrow parameter range.
Using a more detailed model, we found that two modifications of the fish locomotor system transform it into a model reproducing the shrimp goby behavior. These modifications are: 1. modifying the central pattern generator which drives swimming such that it is quiescent when receiving no inputs; 2. introducing a direct sensory input to this central pattern generator, bypassing the Mauthner cells.

Keywords Mauthner neuron · Goby · Shrimp-goby · Symbiosis · Neural simulation · Brain

1 Introduction

The escape behavior in fishes is a behavioral pattern which allows the animal to quickly escape an approaching threat (Eaton et al., 1981). It is a stereotyped movement performed at high speed, with high adaptive value. Failure to perform the escape behavior at the appropriate moment and at high speed can lead to the fish becoming the victim of predation, and hence lead to its death. This escape behavior has been extensively studied, both behaviorally as well as neurobiologically, mainly in two teleost species commonly used as laboratory model systems, the zebrafish (*Danio rerio*) and the goldfish (*Carassius auratus*), both freshwater carp-relatives (Class: *Actinopterygii*; Order: *Cypriniformes*; Family: *Cyprinidae*). The following picture emerges of the escape behavior and its neural basis:

Behaviorally, the escape behavior initiates within ~ 5 ms of an auditory, lateral line or visual stimulus with the highly stereotypical C-start behavior, a bending of the fish body away from the side of the threat (Eaton et al., 1981). This initial phase of the escape behavior lasts ~ 30 ms. What follows is a relaxation of that bend, a bend in the opposite direction and a rapid swimming escape into an at least partially random direction (but see Eaton et al., 2001, for arguments for a directionality for this second phase). The complete sequence of the escape behavior typically lasts ~ 100 ms (Eaton et al., 1981).

Communicated by Action Editor: Catherine E Carr.

✉ Klaus M. Stiefel
klaus@neurolinx.org

[1] Department of Mathematics, University of Pittsburgh, Pittsburgh, USA

[2] Neurolinx Research Institute, La Jolla, USA

[3] Institute of Environmental and Marine Sciences, Silliman University, Dumaguete, Philippines

Published online: 17 May 2021

The neurobiological basis of the fish escape behavior is the activity of the Mauthner cell system (Hale et al., 2016; Medan & Preuss, 2014; Zottoli & Faber, 2000). The Mauthner cells are a pair of large neurons often considered to be *command neurons*, located in the fish hindbrain, which receive sensory input from the visual, auditory and lateral line sensory systems. A strong, sudden bout of sensory input triggers a spike in a Mauthner cell, which then activates the downstream locomotory systems in the spinal cord which in turn evoke the escape behavior described above. The Mauthner neurons in the right and left hemispheres of the brain mutually inhibit each other through a set of inhibitory interneurons, hence assuring that the escape is fully committed to one side of the fish. The Mauthner cell is not the only neuron connecting sensory input to the escape motor-system, with several additional hindbrain neurons providing redundant paths (Eaton et al., 2001). The Mauthner cells are hence not command neurons in the strict sense, but nevertheless key elements in the fast execution of the escape behavior.

This is the behavioral and neurobiological picture which emerges from studies in the aforementioned goldfish and zebrafish. However, teleost fishes are an extremely diverse groups of animals with over 20,000 descried species, and this biodiversity is mirrored by a large diversity of variants of fish escape behavior (for example see Eaton et al., 1977, Fig. 1). These variants of the escape behavior serve the ecological situations of the respective fishes, such as the tail-first retreat into a burrow of many Anguliformes (eel-like fishes), or the slow turn which aims their venomous fin spines at the threat in the case of many Scorpaeniformes (scorpionfish relatives, Eaton et al., 1977, Fig. 1).

A specialized case of fish behavior in response to threats is seen in the 120 + species of gobies (Class Actinopterygii, Order: Perciformes, Family: Gobiidae) which live in mutualistic symbiosis with alpheid shrimp (Class: Malacostraca, Order: Decapoda, Family: Alpheidae). These fish share a burrow with the shrimp, into which both animals retreat when a predatory fish approaches (Karplus, 1981; Karplus et al., 1981; Karplus & Thompson, 2011; Lyons, 2012). The mutualist symbiosis between the goby and the shrimp involves a division of labor: the crustacean excavates the burrow, and the goby acts as a sentinel at the entrance of the burrow, warning the shrimp of dangers. While the shrimp is not blind, its eye-sight is limited (Zeng & Jaafar, 2012), and it depends on the goby for advanced warnings of approaching dangers. The crustacean emerges from regular trips underground pushing excavated sand and rubble only when cleared to do so by the goby. The shrimp-associated goby does not have an enlarged visual system in comparison to not shrimp-associated gobies (which are the majority of goby species, Stiefel & Reyes, 2018), however the goby visual system is well developed, and the eyes are large in relation to the head of the fish. As a consequence of the mutualist symbiosis, the pair can settle otherwise feature-less sandy areas devoid of hiding places; The burrow constructed by the shrimp, and the warnings signaled by the goby allow their existence in this habitat otherwise too dangerous for small fishes and crustaceans.

To communicate the approach of threats from the goby to the shrimp, a tactile communication system exists between the partners in the symbiosis (Preston, 1978; Karplus, 1979; Karplus & Thompson, 2011). The shrimp almost continuously touches the dorsal, ventral and anal fins of the goby with one of its antennae when it is above ground. In this way, it can read the body language of the fish. A severe threat causes the goby to quickly escape into the burrow head-first (Fig. 1, see also https://www.youtube.com/watch?v=vtz8j5sUwrM). This behavior keeps the shrimp from emerging above ground as well, and both animals remain in the burrow for several minutes before re-emerging. This response to a severe threat is most likely a variant of the basal fish escape behavior (Fig. 1; duration from the initiation of movement to the completion of the turn ~ 25 ms), albeit with the direction of the escape always directed at the entrance of the burrow. Goby escape behavior has been described in detail (*Gobius niger,* Turesson et al., 2009; a non-shrimp-associated goby) and is deemed Mauthner-cell mediated.

In addition to the escape into the burrow, a novel type of behavior has evolved in gobies engaged in a symbiosis with a shrimp, the "tail flick", a brief, fast oscillation of the paired (dorsal, caudal and anal) fins. Perceived by the shrimp through its constant contact with the shrimp when outside the burrow, this is a tactile warning conveyed from the goby to the shrimp in response to an intermediate-level threat. In contrast to the preparatory movements described in Turesson et al. (2009) which are described as "slow and subtle movement of the tail", the tail-flick is fast, involves multiple back-and-forth movements of the tail, and usually does not result in a change in the tail posture after completion of the movement. The tail-flick response signals threats of a severity below those warranting a full escape response, the aforementioned escape into the burrow. Such threats could be a threatening predator sighted further away, approaching more slowly, or smaller in size than a threat which would elicit a full escape response. In response to its tactile perception of a tail-flick, the shrimp reduces its excursions out of the burrow. This tactile communication system is behaviorally well characterized and has been intensively researched since the 1970s (Preston, 1978; Karplus, 1979; Karplus & Thompson, 2011). To our knowledge, no published neurophysiological recordings exist from the brains of shrimp-associated gobies. Karplus (1979) states: "A total of 162 warning signals [tail-flicks] were recorded during 20 h of observations. Signals were only given by the goby while antenna1 contact was maintained between goby and shrimp. The number of signals per series varies from 1 to 9 with a mean of 1.7 signals per series (S.D.El.1). 93% of all the

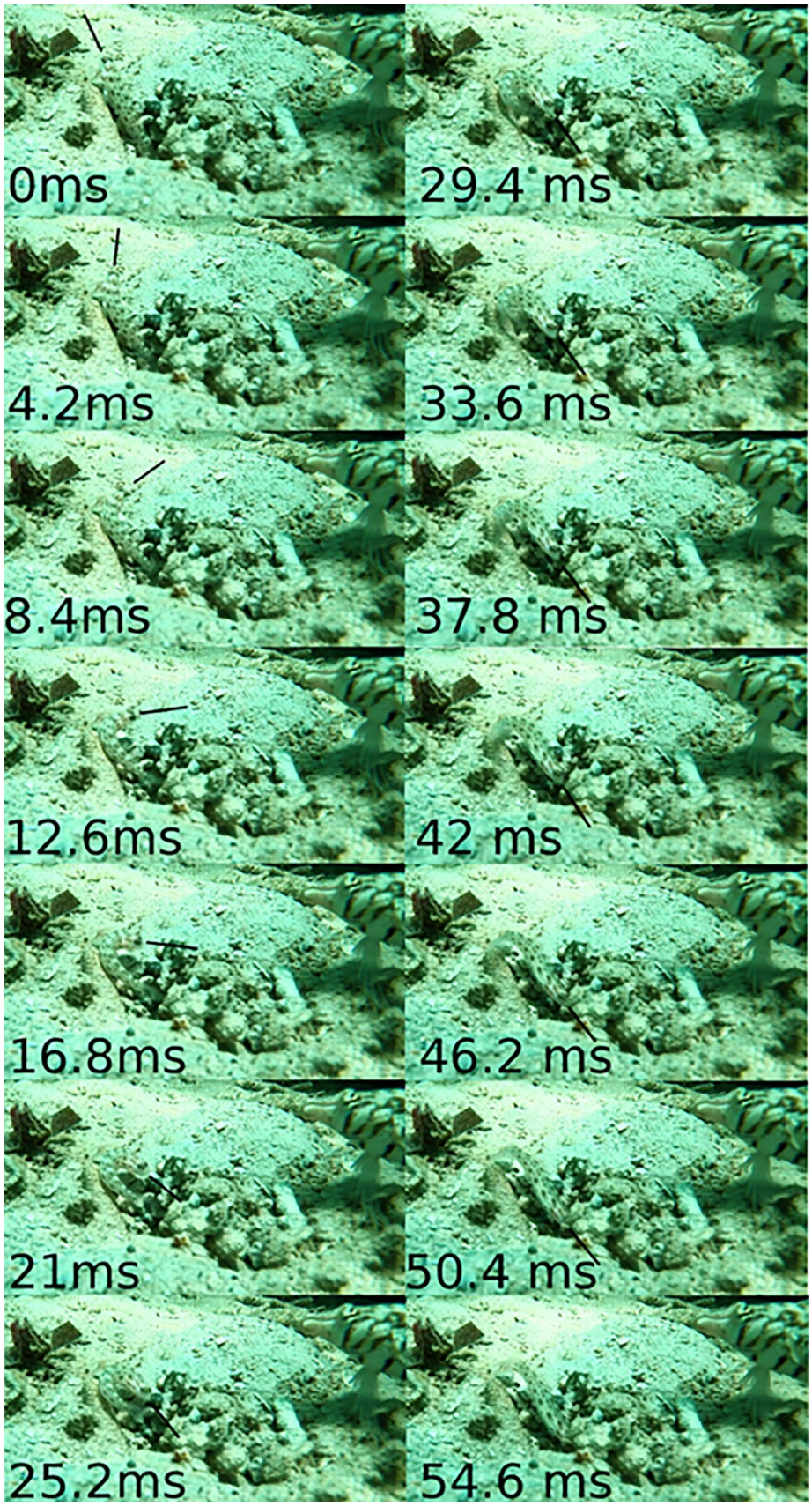

Fig. 1 Escape behavior of a goby, *Ctenogobiops crocineus* into its burrow. Successive frames of a high speed-recording are shown. A piscivorus sandperch, Parapercis cylindrica, is approaching the goby from the right, triggering the escape behavior. Filmed in a seagrass meadow near Bolinao, Pangasinan province, Philippines, on scuba at a depth of 2 m by placing a GoPro Hero6 camera in front of the burrow. The frame rate of the camera was set to 240 fps, corresponding to 4.2 ms per frame. The line indicates the head-direction of the goby. The turn of the fish was completed at 25.2 ms, the head of the fish entered the burrow at 50.4 ms. For the full recording see: https://www.youtube.com/watch?v=vtz8j5sUwrM

signals (7.4 signaldh) were given in response to the approach of a fish to the burrow entrance. During the remaining 7% of the signals no intruding fish were observed. These signals were probably given in response to intruders not noticed by the observer.".

The tail-flick was enacted in response to large fishes, and in response to medium-sized fishes which are either piscivores or disturbing the substrate (goatfish). Small fish did not elicit a tail-flick.

It is the novel emergence of the intermediate (tail-flick) response which we attempt to explain in this theoretical study as an evolutionary modification of the basal fish locomotor system. Specifically, we explore the possible modifications which could change its dynamics towards low-amplitude oscillation at an intermediate input strength. For this purpose we use numerical simulations of the fish locomotor system.

2 Methods

We simulated the basal fish locomotor system plus the Mauthner cell system, such as found in the zebrafish, and possible versions of the derived system as found in burrow-dwelling, shrimp associated gobies. For this purpose we used numerical models of the fish locomotor system, with the individual neurons modeled as excitable or oscillating point neurons. We did not simulate the dendrites of individual neurons, like Mauthner neurons, in detail as in (Mäki-Marttunen & Medan, 2014), rather we modeled the individual neurons as point neurons based on the Morris-Lecar model (Ermentrout & Terman, 2010). We believe that this level of abstraction is appropriate for the questions we ask which likely do not involve changes in intracellular dynamics: We try to figure out what the possible changes in the fish locomotor system are, so that it produces behavior akin to the shrimp-goby escape & communication system. We assume that changes in cellular excitability and synaptic connectivity are necessary and sufficient.

We compared a simple model, consisting of only two inhibitory coupled Mauthner cells, and a complex model, incorporating the Mauthner cell system plus downstream components of the fish locomotor system, such as the central pattern generator (CPG).

2.1 Simple model

In this model, two Mauthner cells are receiving external inputs and are coupled by inhibitory interneurons. The Mauthner cell activation decays over time with the time constant τ_z. The magnitude of the inhibition is controlled by the parameters β, r, and g. The variable c represents ambient noise in the system.

Functions:

$$f(x) = \frac{1}{1+e^{-x}} \tag{1}$$

$$Input(x,t) = xu\left(t - t_{on}\right)u\left(t_{on} + dur - t\right) \tag{2}$$

where

$$u(x) = \begin{cases} 0 \text{ if } x < 0 \\ 1 \text{ if } x \geq 0 \end{cases}$$

Mauthner cells:

$$M_l^{'} = -M_l + f\left(Input\left(I_{max,}t\right) - gY_r - rY_l - \beta Z_l + c\right) \tag{3}$$

$$M_r^{'} = -M_r + f\left(Input\left(I_{max,}t\right) - gY_l - rY_r - \beta Z_r + c\right) \tag{4}$$

Inhibitory neuron

$$Y_l^{'} = \left(-Y_l + max\left\{\left(M_l + \zeta Input\left(I_{max},t\right),0\right\}\right)/\tau_y \tag{5}$$

$$Y_r^{'} = \left(-Y_r + max\left\{\left(M_r + \zeta Input\left(I_{max},t\right),0\right\}\right)/\tau_y \tag{6}$$

Mauthner adaptation process

$$Z_l^{'} = \left(M_l - Z_l\right)/\tau_z \tag{7}$$

$$Z_r^{'} = \left(M_r - Z_r\right)/\tau_z \tag{8}$$

Parameter values

$I_{max} = 4$, $g = 6$, $r = 0.3$, $\beta = 1.5$, $\tau_z = 5$, $q = 0.99$, $c = 1$, $ton = 25$, $dur = 200$, $\tau_y = 0.2$, $\zeta = 0.01$.

2.2 Complex model

Our complex model is based on the model of the zebrafish fish locomotor system, plus Mauthner cell system, as proposed by Miller et al. (2017; see also Park et al., 2018; Fig. 2). This model was originally designed to model the plasticity of the Mauthner system dependent on the social status of a fish; However, with some modifications it is also applicable to the questions we investigate here. Below we will first outline the equations of the basal version of this model, and then the key modifications we made to obtain dynamics akin to the tail-flick response.

The complex model explicitly simulates the Mauthner cells, interneurons, the fast motorneurons, slow motorneurons, and the swimming central pattern generators (CPGs). Each cell type is governed by ordinary differential equations (ODEs) and functions accessory to these ODEs. The equations were:

Mauthner cell functions:

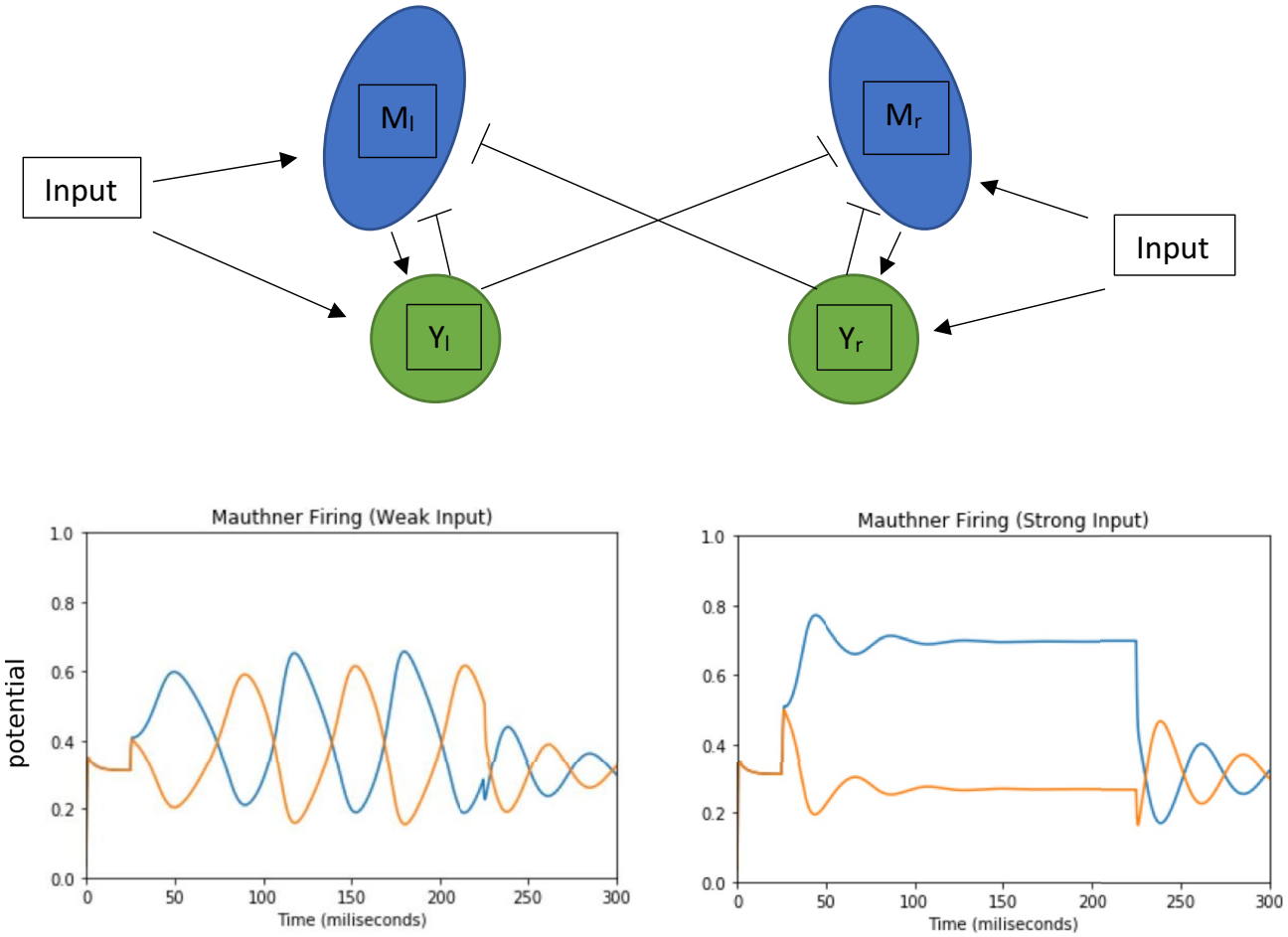

Fig. 2 Simple model outline (top), and oscillatory behavior akin to the tail-flick behavior (bottom). The potential (y-axis) is an abstract version of a membrane potential, not measured in mV

$$m_{inf}(v) = 0.5\left(1 + \tanh\left(\left(v - v_{f1}\right)/v_{f2}\right)\right) \tag{9}$$

$$w_{inf}(v) = 0.5\left(1 + \tanh\left(\left(v - v_{f3}\right)/v_{f4}\right)\right) \tag{10}$$

$$\tau_w(v)\frac{1}{\cosh\left(\left(v - v_{f3}\right)/\left(2v_{f4}\right)\right)} \tag{11}$$

$$mw_{inf}(v) = 0.5\left(1 + \tanh\left(\left(v - v_{f3}\right)/m_{vf4}\right)\right) \tag{12}$$

$$m\tau_w(v)\frac{1}{\cosh\left(\left(v - v_{f3}\right)/2v_{f4}\right)} \tag{13}$$

$$m_{sinf}(v) = \frac{1}{1 + \exp\left(-\left(v + \theta_s\right)/m_{ss}\right)} \tag{14}$$

$$m_{syn1} = mg_{syn}ms_2\left(m_{v1} - mv_{syn}\right) \tag{15}$$

$$m_{syn2} = mg_{syn}ms_1\left(m_{v2} - mv_{syn}\right) \tag{16}$$

$$pul(t) = u(t)u(dur - t) \tag{17}$$

Mauthner cell differential equations:

$$m_v[1,2]' = \left(mb_{iapp} + m_{stim}[j]pul\left(t - stimon[j]\right) - g_{ca}m_{inf}(m_v[j])\left(m_v[j] - v_{ca}\right)\right) - g_k m_w[j]\left(m_v[j] - v_k\right) - g_l\left(m_v[j] - v_k\right) \tag{18}$$

$$-m_{syn}[j] - gkca\left(m_{ca}[j]/\left(m_{ca}[j]/(m_{ca}[j] + ca_0)\right)\left(m_v[j] - v_k\right)\right)/cmm_w[1,2]' = m_\phi\left(m_{winf}m_v[j] - m_w[j]\right)/\left(m_{\tau w}m_v[j]\right) \tag{19}$$

$$m_s[1,2]' = m_\alpha\left(1 - m_s[j]\right)ms_{inf}m_v[j] - m_\beta m_s[j] \tag{20}$$

$$m_s[1,2]' = m_\alpha\left(-\mu g_{ca} m_{inf} m_v[j]\left(m_v[j] - v_{ca}\right) - m_{ca}[j] kca\right) \tag{21}$$

Fast motor neuron differential equations:

$$\begin{aligned} fmn_v[1,2]' = {} & fmn_{iapp} - g_{ca} m_{inf} fmn_v[j]\left(fmn_v[j] - v_{ca}\right) \\ & - g_k fmn_w[j]\left(fmn_v[j] - v_k\right) - g_l\left(fmn_v[j] - v_l\right) \\ & - fmn_{syn}[j] - gkca\left(fmn_{ca}[j] / \left(fmn_{ca}[j] + ca_0\right)\right) \\ & \left(fmn_v[j] - v_k\right)/cm \end{aligned} \tag{22}$$

$$fmn_w[1,2] = fm_\phi\left(w_{inf} fmn_v[j] - fmn_w[j]\right)/\left(\tau_w fmn_v[j]\right) \tag{23}$$

$$fmn_{ca}[1,2]' = fm_\epsilon\left(-\mu g_{ca} m_{inf} fmnv[j]\left(fmn_v[j] - v_{ca}\right) - fmn_{ca}[j] kca\right) \tag{24}$$

Inhibitory interneuron functions:

$$mti_{syn} = mtig_{syn}\left(m_{s1} + m_{s2}\right)\left(in_v - iv_{syn}\right) \tag{25}$$

$$mti_{syn}(v) = \frac{1}{\left(1 + exp\left(-\left(v + \theta_s\right)/mtis\right)\right)} \tag{26}$$

$$its_{syn1} = i2mng_{syn} in_s\left(smnv_{v1} - i2mng_{syn}\right) \tag{27}$$

$$its_{syn2} = i2mng_{syn} in_s\left(smnv_{v2} - i2mng_{syn}\right) \tag{28}$$

Inhibitory interneuron differential equations:

$$\begin{aligned} in_v' = {} & \left(iiapp + g_{ca} m_{in} in_v\left(in_v - v_{ca}\right) - g_k in_w\left(in_v - v_k\right)\right. \\ & - gl\left(in_v - v_l\right) - mti_{syn} - gkca\left(in_{ca}\left(in_{ca} + ca_0\right)\right) \\ & \left.\left(in_v - v_k\right)\right)/cm \end{aligned} \tag{29}$$

$$in_w' = i_\phi\left(w_{inf} in_v - in_w\right)/\left(\tau_w in_v\right) \tag{30}$$

$$in_w' = i_{alpha}\left(1 - in_s\right)\left(mtis_{inf} in_v - i_\beta in_s\right) \tag{31}$$

$$in_w' = i_\epsilon\left(-\mu g_{ca} m_{inf} in_v\left(in_v - v_{ca}\right) - in_{ca} kca\right) \tag{32}$$

CPG functions:

$$cpg_{syn1} = cpg_{syn} cpg_{s2}\left(cpg_{v1} - cpg_{vsyn}\right) \tag{33}$$

$$cpg_{syn2} = cpg_{syn} cpg_{s1}\left(cpg_{v2} - cpg_{vsyn}\right) \tag{34}$$

$$i2cpg_{syn1} = i2cpgg_{syn} in_s\left(cpg_{v1} - i2cpg_{vsyn}\right) \tag{35}$$

$$i2cpg_{syn2} = i2cpgg_{syn} in_s\left(cpg_{v2} - i2cpg_{vsyn}\right) \tag{36}$$

CPG differential equations:

$$cpg_x' = -cpg_x/\tau_{cpgx} + (stimon) pul(t - stimon)\left(1 - cpg_x\right) \tag{37}$$

$$\begin{aligned} cpg_v[1,2]' = {} & \left(cpg_{iapp} + cpg_x - g_{ca} m_{inf} cpg_v[j]\left(cpg_v[j] - v_{ca}\right)\right. \\ & - g_k cpg_w[j]\left(cpg_v[j] - v_k\right) - g_l\left(cpg_v[j] - v_l\right) - cpg_{syn}[j] \\ & - i2cpg_{syn}[j] - gkca\left(cpg_{ca}[j] / \left(cpg_{ca}[j] + ca_0\right)\right) \\ & \left.\left(cpg_v[j] - v_k\right)\right)/cm \end{aligned} \tag{38}$$

$$cpg_w[1,2]' = cpg_\phi\left(w_{inf} cpg_v[j] - cpg_w[j]\right)/\left(\tau_w cpg_v[j]\right) \tag{39}$$

$$cpg_w[1,2]' = cpg_\alpha\left(1 - cpg_s[j]\right) s_{inf}\left(cpg_v[j]\right) - cpg_\beta cpg_s[j] \tag{40}$$

$$cpg_w[1,2]' = cpg_\epsilon\left(-\mu g_{ca} m_{inf} cpg_v[j]\left(cpg_v[j] - v_{ca}\right) - cpg_{ca}[j] kca\right) \tag{41}$$

Slow motor neuron functions:

$$smn_{syn1} = smng_{syn} cpg_{s1}\left(smn_{v1} - smn_{vsyn}\right) \tag{42}$$

$$smn_{syn2} = smng_{syn} cpg_{s2}\left(smn_{v2} - smn_{vsyn}\right) \tag{43}$$

Slow motor neuron differential equation:

$$\begin{aligned} smn_v[1,2]' = {} & \left(smn_{iapp} - g_{ca} m_{inf} smn_v[j]\left(smn_v[j] - v_{ca}\right)\right. \\ & g_k smn_w[j]\left(smn_v[j] - v_k\right) - smn_{syn}[j] - its_{syn}[j] \\ & - (gkca) smn_{ca}\left(smn_{ca}[j] / \left(smn_{ca}[j] + ca_0\right)\right) \\ & \left.\left(smn_v[j] - v_k\right)\right)/cm \end{aligned} \tag{44}$$

$$smn_v[1,2]' = sm_\phi\left(w_{inf} smn_v[j] - smn_w[j]\right)/\left(\tau_w smn_v[j]\right) \tag{45}$$

$$smn_w[1,2]' = sm_\epsilon\left(-\mu g_{ca} m_{inf} smn_v[j]\left(smn_v[j] - v_{ca}\right) - smn_{ca}[j] kca\right) \tag{46}$$

2.3 Parameters

$v_{f1} = -1.2$, $v_{f2} = 18$, $v_{f3} = 12$, $v_{f4} = 17.4$, $g_{ca} = 4$, $v_{ca} = 120$, $gl = 2$, $gk = 8$, $v_l = -60$, $v_K = -84$, $iapp = 45$, $\varphi = 0.23$, $ss = 0.2$, $\theta_s = 0$, $v_{syn} = 30$, $g_{syn} = 0.1$, $cm = 20$, $kca = 1$, $gk_{ca} = 0.25$, $\mu = 0.2$, $ca_0 = 10$, $mv_{syn} = -50$, $mg_{syn} = 0.5$, $m_\beta = 0.08$, $m_\alpha = 10$, $miapp1 = 3$, $miapp2 = 0$, $mbiapp = 40.5$, $mss = 4$, $mv_{f4} = 17$, $m_\epsilon = 0.005$, $m_\varphi = 0.23$, $fmngsyn = 0.4$, $fmnv_{syn} = 30$, $fmniapp = 38$, $fm_\epsilon = 0.005$, $fm_\varphi = 0.225$, $2agfmn = 0$, $fmn_w = 0.5$, $mtig_{syn} = 0.2$, $ivsyn = 30$, $i_\alpha = 10$, $i_\beta = 0.00035$, $iiapp = 40.4$, $mtis = 1$, $i_\epsilon = 0.005$, $i_\varphi = 0.225$, $2agin = 0$, $i2mng_{syn} = 0.6$, $i2mnv_{syn} = -50$, $iinw = 1$, $cpgv_{syn} = -30$, $cpgg_{syn} = 0.3$, $cpg_\beta = 0.2$, $cpg_\alpha = 10$, $cpg_{iapp} = 44.7$, $cpg_\epsilon = 0.005$, $cpg_\varphi = 0.23$, $i2cpgg_{syn} = 0$, $i2cpgv_{syn} = -50$, $smng_{syn} = 0.37$, $smnv_{syn} = 25$, $smn_{iapp} = 40.4$, $sm_\epsilon = 0.005$, $sm_\varphi = 0.23$, $\tau_{cpgx} = 300$, $dur = 50$, $stimon = 2000$, $\tau_{cpgx} = 300$.

2.4 Minor modifications of the original model

The equations of Miller et al. (2017) were initially slightly modified to better fit our purpose. Specifically, their model contained four fast and slow motor neurons. This was simplified to one pair of fast and slow motorneurons per Mauthner cell. Additionally, the equations in the original model relating to social dominance were omitted, an aspect of the Mauthner system irrelevant to the questions we address here.

Furthermore, in the original Mauthner cell equation in Miller et al. (2017) the Mauthner cells are triggered at a range of time intervals resulting in repeated firing. We simplified this so that they only activate at one point (given by the new parameter stimon) for a set duration (given by the parameter dur). The function pul(t) in the ODE governing the Mauthner cells (given above) is given by:

$$pul(t) = u(t)u(dur - t)$$

Concurrent with these changes, we replaced the set of stimulus parameters in Miller et al. (2017), stim[1–18], with a set of two parameters m_{stim1}, m_{stim2}. These parameters apply to the corresponding Mauthner cell. The Mauthner cell will fire and activate the fast motor neuron (i.e. the strong response will occur) whenever $\max\{m_{stim1}, m_{stim2}\} > \sim 6$.

The purpose of these modifications was to eliminate the aspects of the stimulation specific to the input stimulus in Miller et al. (2017), and to eliminate the components of the model related to the simulations of social dominance, which are not relevant for out study. The basic dynamics of the fish locomotor system and Mauthner cell system remained intact, however. These modifications hence resulted in the ***basal model, corresponding to the neural dynamics underlying the escape behavior in a zebrafish***.

2.4.1 Two key modifications

We introduced ***two key modifications into the basal model*** so that it produces the escape behavior and the ***tail-flick behavior of shrimp-associated gobies*** in response to strong, and weak stimuli, respectively.

Firstly, in the original model by Miller et al. (2017), the CPG will run perpetually, regardless of the amount of stimulus being applied. This corresponds to continuous swimming by the zebrafish; in contrast, the benthic shrimp goby usually rests stationary in front of its burrow. Hence we lowered the parameter cpg_{iapp}, the tonically applied input current, from 45 to 44.7 ***so that the CPG will not activate at all on its own.*** This leads to a motor system model where the benthic goby swims in response to specific stimuli, as opposed to the near-constant swimming seen in mid-water zebrafish.

Secondly, we introduced a new connection, from the input to the CPG. This connection is represented by the term containing the variable cpg_x. Through this novel connection, a quick pulse that decays exponentially whenever the Mauthner cell system receives stimuli is sent to the CPG. The CPG will activate whenever the sum of cpg_{iapp} and cpg_x is greater than ~ 44.8 (Fig. 3).

This way, the CPG will not activate at all in the case of no stimulus being applied, and thus neither will the slow motor neurons. When a weak stimulus is applied the CPG and the slow motor neurons will respond for a restricted time period. This corresponds to the tail-flick response.

In the case of a strong stimulus, the slow motor neurons are inhibited. The time constant for the direct activation of the CPG was carefully chosen to be $\tau_{cpgx} = 300$, long enough for the slow motor neurons to activate, but not so long that the tail-flick response would initiate after the end of inhibition in the case of a strong stimulus. Hence, by introducing one additional connection from the sensory input to the CPG, and by setting the CPG's ground state to quiescent, we have modified the Mauthner system model so that it displays a response to intermediate stimulus strengths.

2.5 Numerical simulations

All simulations were conducted in XPP (Ermentrout, 2002), with a 0.01 ms step-size and using the forward Euler numerical algorithm. The simulation code is available from the authors upon request and on ModelDB (https://senselab.med.yale.edu/modeldb/).

2.6 Underwater videography

The frames of the high-speed video recording shown in Fig. 1 were recorded with a GoPro HERO6 camera at a resolution of 1080 × 1920 pixels, and a frame rate of 240 frames per second. The field sites for the recordings were near the Marine Biological Laboratory of the University of the Philippines in Bolinao, Pangasinan province. Cameras were carefully placed by scuba divers next to the shrimp-goby burrows, and divers subsequently left to minimize disturbance of the animals. Footage was recorded until a predatory fish approached the burrow and the goby initiated an escape response (as in Fig. 1), or, in the absence of a predatory fish, until the escape response was evoked by the eventual approach of a diver.

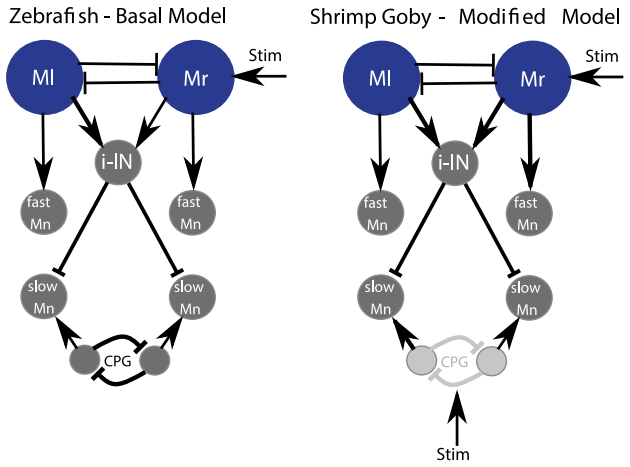

Fig. 3 Complex model outline. A: the basal model corresponding to the zebrafish escape circuit, according to Miller et al. (2017). B: The modified model, corresponding to the shrimp-goby system. In this model, the CPG (grayed out) is inactive at rest, and the sensory input reaches the CPG directly (second ***stim*** arrow)

3 Results

3.1 Simple model

The simple model (Fig. 2) reproduced a fast oscillation of the two Mauthner cells, as would give rise to the tail-flick behavior. In these simulations, one Mauthner cell receives a stimulus with an amplitude of I_{max}, while the other will receive a fraction of that stimulus strength, q, giving rise to a stimulus-strength asymmetry. If q is less than ~ 0.97, the asymmetry will be too great and oscillations will not occur. Hence, while this model can produce oscillations of an abstracted version of the fish motor systems as seen in a tail-flick behavior, it only does so in a rather narrow parameter range of, with a similarity of activation strength between the Mauthner cells needing to be within 3%. We therefore looked at a more complex model to reproduce the tail-flick response in a more stable, and hence biologically realistic manner.

In the case of a strong stimulus, the simple model successfully reproduces the desired behavior. The firing onset time is shorter, and the firing rate of one Mauthner cell will greatly surpass that of the other, and thus lead to an asymmetrical response. This is the fast C-start escape that will allow the goby to retreat into the shrimp's burrow. The fact that the Mauthner cells in this model fire repetitively is also an aspect of this model which makes it less realistic. The firing threshold of this model is dependent on both the absolute value as well as the slope of the simulated voltage.

3.2 Complex model

The simulations of the basal version of the complex model reproduced neural dynamics corresponding to a C-start escape response triggered by a strong stimulus. This model does not respond to a situation with no, or a weak stimulus. This situation corresponds to the neural dynamics in the zebrafish and reproduces the findings of Miller et al. (2017) (Fig. 4).

The modified complex model transformed the dynamics of the fish locomotor system in several ways. In the trivial case of zero input, neither the Mauthner cell nor the CPG will activate at all. Thus, the goby will remain still, as it is observed during the majority of its time (Karplus & Thompson, 2011; Lyons, 2012; personal observations, K.M.S.). The CPG driving the swimming behavior is not continually active in this model, since the novel connection cpg_x requires a nonzero input from the parameter $m_{stim}[1,2]$ to initiate activity of the CPG.

In the case of a weak input, the Mauthner cells will not activate and thus neither will the downstream fast motor neurons. The CPG, however, will be activated for a short period of time due to the activation of via the newly introduced direct connection, governed by the parameter cpg_x (the arrow at the bottom of the diagram denoted Stim in Fig. 2). This results in an oscillation of the slow motor neurons for a period of time similar to the CPG's activation. The movement evoked by the slow motor neurons corresponds to the tail-flick response of the goby (Fig. 5). The weak input corresponds to a more distant or smaller approaching threat; We do not simulate in detail how the weak input comes about in the upstream visual, auditory and lateral line systems, which is outside of the level of abstraction chosen in this study.

In the case of a strong input, the Mauthner cell receiving input will fire exactly once, resulting in activation of the corresponding fast motor neuron. The CPG will still be activated via the direct connection, during a time-span given by the decay of cpg_x. However, despite this the slow motor neurons will never activate since they are inhibited by interneurons downstream of the Mauthner neurons throughout this time period (Fig. 2, Fig. 5). This response to a strong stimulus corresponds to the fast C-start escape response of the goby.

4 Discussion

We have shown that relatively simple modifications of the basal fish locomotor system can generate dynamics as seen in the escape and communication behavior of shrimp-associated gobies. Only a more complex model, incorporating downstream circuitry, reproduces the observed behavior with a satisfactory degree of biological realism.

Our theoretical predictions are that the shrimp-goby like newly emergent behavior is due to 1. a change in the CPG which keeps it inactive at rest. This is certainly a realistic prediction, since benthic shrimp-gobies typically perch motionlessly in the sand in front of their burrows most of the time (Karplus & Thompson, 2011; Lyons, 2012; for an example of footage of this mostly stationary behavior

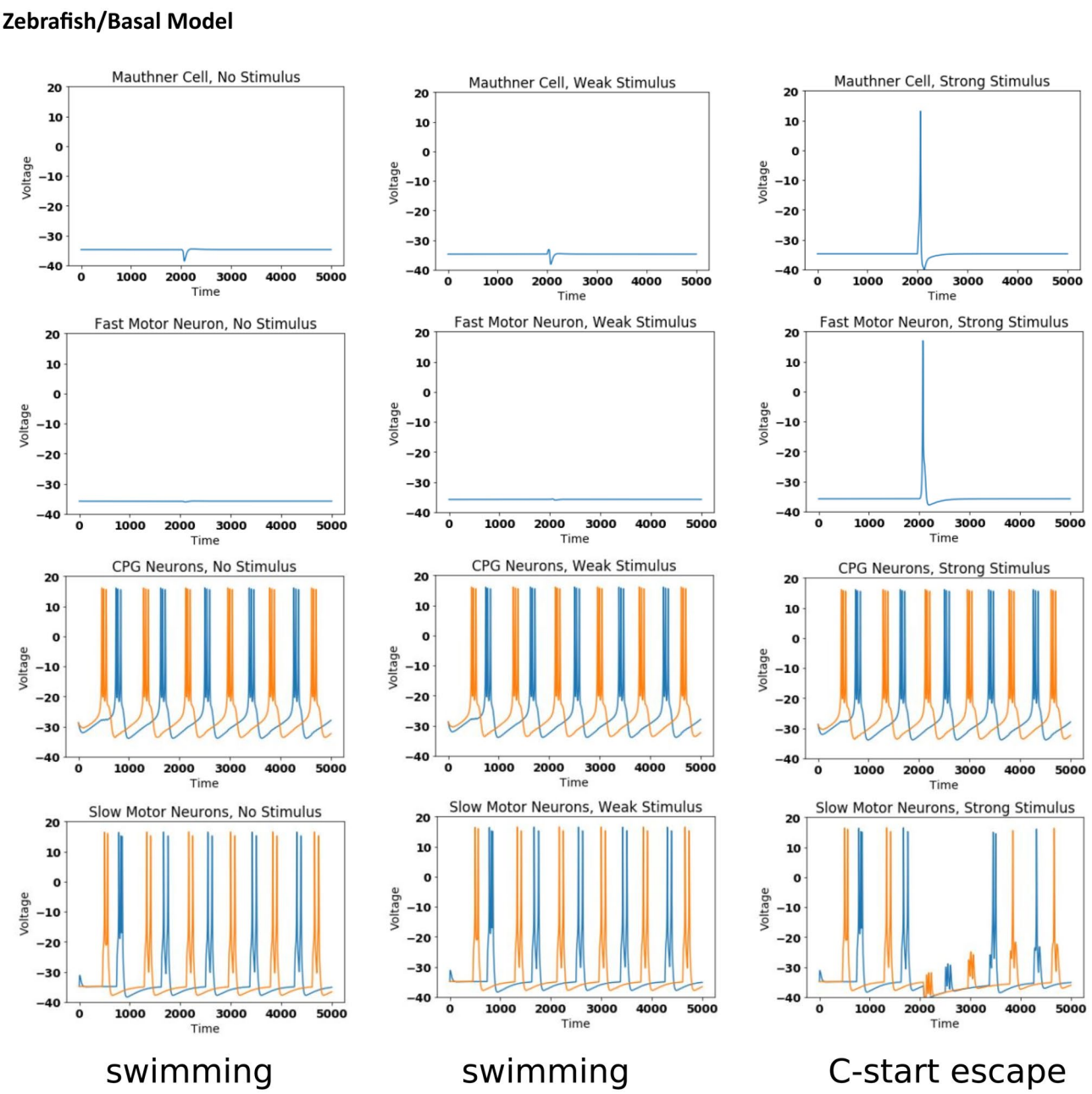

Fig. 4 Complex model simulation results. The base model corresponding to the zebrafish escape response, not stimulated, and stimulated with weak and strong stimuli. Rows: Mauthner cell, fast motor neuron, CPG neuron, slow motor neuron. Columns: no input, weak stimulus, strong stimulus. Voltage traces of the left/right Mauthner cells are shown in orange/blue

see: (https://www.youtube.com/watch?v=oouKWvL0os8). Exceptions are the infrequent feeding excursions, implemented by circuits not treated here, as well as the escape behavior we modeled. This behavior is in contrast to near-continuously swimming fishes like zebrafish where the swimming-CPG is likely near-continuously active.

We furthermore predict that 2. a connection of the sensory input to the CPG exists, bypassing the Mauthner cell. It is unlikely that a direct, mono-synaptic connection from the sensory (visual, auditory, lateral-line) inputs reaches the CPG; However, a multi-synaptic bypass via an intermediate set of neurons is likely.

While our model is agnostic about the nature of these novel connections, there are several anatomical candidates for a novel connection from the sensory systems to the central pattern generator. One are the hindbrain neurons partially redundant with the Mauthner cell, such as the MiD2cm and MiD3cm neurons, discussed in Eaton et al.

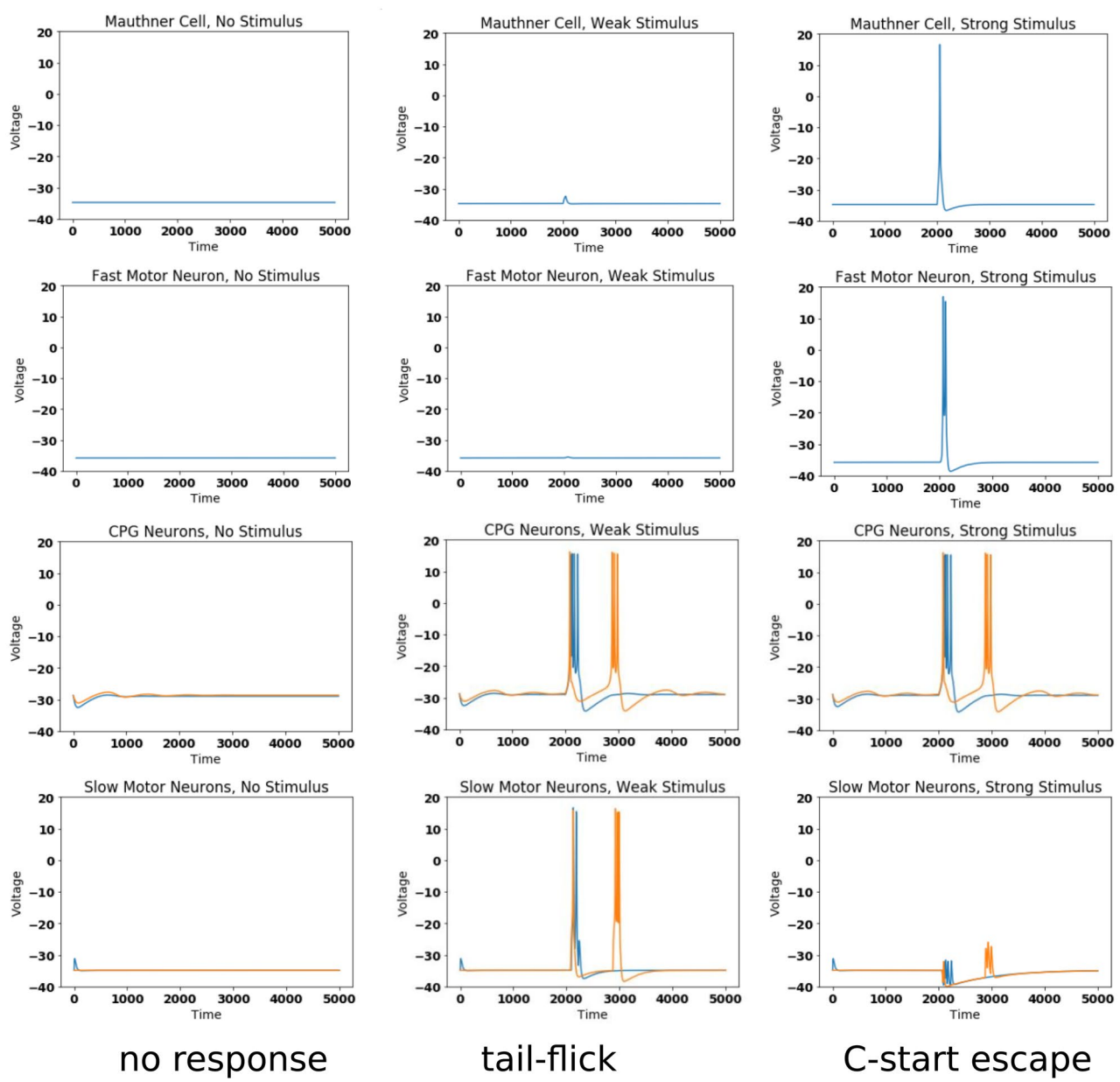

Fig. 5 Complex model simulation results. The modified model corresponding to a full escape response (in response to a strong stimulus) and the tail-flick (in response to a weak stimulus) in shrimp-associated gobies. Figure conventions as in Fig. 3

(2001). These neurons are similar to the Mauthner cell in their position in the hindbrain, similar in the inputs they receive, and also similar, albeit smaller in their morphology. In the goldfish system, they alone (when the Mauthner cell is ablated) enact a slower, weaker version of the escape behavior. Alternatively, the Mauthner cells could duplicate, as is known to occur with a mutation of the notch1a/deadly seven (des) genes in zebra fish, resulting in the development of an extra Mautner cell in cells in rhombomere r4 (Liu et al., 2003). ***A lower threshold for the activation of these hindbrain neurons (MiD2cm and MiD3cm; or duplicated Mauthner cells), paired with their projection to the CPG but not to the fast motorneurons would modify the basal escape-behavior system towards a system with an intermediate tail-flick response, as seen in shrimp-associated gobies***. This is a testable physiological and anatomical prediction of our model. A duplication of a functional element (in this case the pre-existing Mauthner-cell-like MiD2cm

and MiD3cm neurons, or novel duplicated Mauthner cells), followed by a modification of the function of the duplicated element is a common course in evolution at a number of levels of organization (brain regions and pathways: Chakraborty & Jarvis, 2015; genes: Holland & Short, 2008).

Other novel candidate connections linking the sensory systems to the central pattern generator would be direct connections from higher-order visual, auditory and lateral line systems to the CPG.

While the predicted changes in the fish locomotor system produce dynamics akin to the derived escape and communication behavior seen in shrimp gobies, it is conceivable that other, fundamentally different, modifications of the locomotor cell system can equally cause such dynamics. We believe that this is unlikely. We have excluded the possibility that a modification solely at the level of the Mauthner cells can give rise to the observed behavior by studying the simple model presented in this study. Furthermore, any modifications of the basal Mauthner system which result in a not continuously swimming fish, as observed in goby behavior, will need to quiesce the swimming-CPG. And any graded response to a sub-threshold threatening stimulus will have to bypass the all-or-none, spiking Mauthner neurons. Hence any alternative modifications of the fish locomotor satisfying these criteria will very likely be a variants of our model.

As outlined in the introduction, different lineages of fishes show different types of derived escape behavior (Eaton et al., 1977). Further computational studies could play a vital part in predicting which modifications to the basal Mauthner/locomotor systems could produce these ecologically highly relevant types of behavior.

Acknowledgments We would like to thank Ms. Lala Grace Calle, Ms. Dana Manogan, Drs. Nadia Palomar-Abesamis and Dr. Patrick Cabaitan for helpful discussion of the manuscript and the anonymous reviewers for helpful feedback on the first version. We would also like to thank Sungwoo Ahn for the Mauthner cell code for the complex model. G.B.E. would like to thank the National Science Foundation.

Author contributions K.M.S. conceived the idea to the study. J.A.L. and G.B.E. developed the model, wrote and ran the simulations. All authors wrote the manuscript.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

Chakraborty, M., & Jarvis, E. D. (2015). Brain evolution by brain pathway duplication. *Philosophical Transactions of the Royal Society B: Biological Sciences, 370*(1684), 20150056.

Eaton, R. C., Bombardieri, R. A., & Meyer, D. L. (1977). The Mauthner-initiated startle response in teleost fish. *Journal of Experimental Biology, 66*(1), 65–81.

Eaton, R. C., Lavender, W. A., & Wieland, C. M. (1981). Identification of Mauthern-initiated response patterns in goldfish: evidence for simultaneous cinématography and electrophysiology. *Journal of Comparative Physiology, 144*, 521–531.

Eaton, R. C., Lee, R. K. K., & Foreman, M. B. (2001). *The Mauthner cell and other identified neurons of the brainstem escape network of fish, 63*, 467–485.

Ermentrout, B. (2002). *Simulating, analyzing, and animating dynamical systems: a guide to XPPAUT for researchers and students,* (Vol. 14). Siam.

Ermentrout, G. B., & Terman, D. H. (2010). *Mathematical foundations of neuroscience* (Vol. 35). Springer Science & Business Media.

Hale, M. E., Katz, H. R., Peek, M. Y., & Fremont, R. T. (2016). Neural circuits that drive startle behavior, with a focus on the Mauthner cells and spiral fiber neurons of fishes. *Journal of neurogenetics, 30*(2), 89–100.

Holland, L. Z., & Short, S. (2008). Gene duplication, co-option and recruitment during the origin of the vertebrate brain from the invertebrate chordate brain. *Brain, behavior and evolution, 72*(2), 91–105.

Karplus, I. (1981). Goby-shrimp partner specificity. II. The behavioural mechanisms regulating partner specificity. *Journal of Experimental Marine Biology and Ecology*, *51*(1), 21–35.

Karplus, I. (1979). The tactile communication between *Cryptocentrus steinitzi* (*Pisces, Gobiidae*) and *Alpheus purpurilenticularis* (*Crustacea, Alpheidae*). *Zeitschrift für Tierpsychologie, 49*(2), 173–196.

Karplus, I., Szlep, R., & M., Tsurnamal. (1981). Goby-shrimp partner specificity. I. Distribution in the northern Red Sea and partner specificity. *Journal of Experimental Marine Biology and Ecology, 51*(1), 1–19.

Karplus, I., & Thompson, A. (2011). The partnership between gobiid fishes and burrowing alpheid shrimps. *The Biology of Gobies,* 559–607.

Liu, K. S., Gray, M., Otto, S. J., Fetcho, J. R., & Beattie, C. E. (2003). Mutations in deadly seven/notch1a reveal developmental plasticity in the escape response circuit. *Journal of Neuroscience, 23*(22), 8159–8166.

Lyons, P. (2012). *The evolution of mutualism between alpheid shrimp and gobiid fishes: a balance between benefits and costs* (Doctoral dissertation, The Graduate School, Stony Brook University: Stony Brook, NY.).

Mäki-Marttunen, T., & Medan, V. (2014). A computational model on the goldfish Mauthner cell, BMC *Neuroscience, 15*(Suppl 1) 97.

Medan, V., & Preuss, T. (2014). The Mauthner-cell circuit of fish as a model system for startle plasticity. *Journal of Physiology-Paris, 108*(2–3), 129–140.

Miller, T. H., Clements, K., Ahn, S., Park, C., Ji, E. H., & Issa, F. A. (2017). Social status-dependent shift in neural circuit activation affects decision making. *Journal of Neuroscience, 37*(8), 2137–2148.

Park, C., Clements, K. N., Issa, F. A., & Ahn, S. (2018). Effects of social experience on the habituation rate of zebrafish startle escape response: empirical and computational analyses. *Frontiers in neural circuits, 12*, 7.

Preston, J. L. (1978). Communication systems and social interactions in a goby-shrimp symbiosis. Animal Behaviour, 26, 791–802.

Stiefel, K. M., & Reyes, R. B. (2018). The marine goby–alpheid shrimp symbiosis does not correlate with larger fish eye size. *bioRxiv*, 329094.

Turesson, H., Satta, A., & Domenici, P. (2009). Preparing for escape: anti-predator posture and fast-start performance in gobies. *Journal of Experimental Biology, 212*(18), 2925–2933.

Zeng, Y., & Jaafar, Z. (2012). Visual acuity of the goby-associated shrimp, *Alpheus rapax Fabricius*, 1798 (*Decapoda, Alpheidae*). *Crustaceana, 85*(12–13), 1487–1497.

Zottoli, S. J., & Faber, D. S. (2000). Review: the mauthner cell: what has it taught us? *The Neuroscientist, 6*(1), 26–38.