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# Hippocampus, Amygdala and Basal Ganglia Based Navigation Control

Ansgar Koene and Tony J. Prescott

Adaptive Behaviour Research Group, Sheffield University,
Western Bank, S10 2TP Sheffield, UK
{A.Koene,T.J.Prescott}@sheffield.ac.uk
http://www.abrg.group.shef.ac.uk/

**Abstract.** In this paper we present a novel robot navigation system aimed at testing hypotheses about the roles of key brain areas in foraging behavior of rats. The key components of the control network are: 1. a Hippocampus inspired module for spatial localization based on associations between sensory inputs and places; 2. an Amygdala inspired module for the association of values with places and sensory stimuli; 3. a Basal Ganglia inspired module for the selection of actions based on the evaluated sensory inputs. By implementing this Hippocampus-Amygdala-Basal Ganglia based control network with a simulated rat embodiment we intend to test not only our understanding of the individual brain areas but especially the interaction between them. Understanding the neural circuits that allows rats to efficiently forage for food will also help to improve the ability of robots to autonomously evaluate and select navigation targets.

**Keywords:** Action selection, navigation, biologically inspired, Hippocampus, Amygdala, Basal Ganglia, place value association.

## 1 Introduction

Efficient foraging behavior relies on a combination of spatial cognition, motivation, and goal-directed navigation in order to maximize the chances of quickly finding sufficient food. Choosing an optimal foraging route requires an evaluation of the relative worth of potential food locations as well as the ability to successfully navigate to the chosen locations.

In this study we combined neurophysiological data and computational neuroscience methodologies to develop a better understanding of the brain systems underlying spatial representation and decision-making in foraging rats and construct a novel robot navigation system based on this understanding. Specifically we focused on the hippocampus-amygdala-basal ganglia complex of rats.

Electrophysiological experiments with rats led to the discovery that in a subset of neurons in the hippocampal region the firing rate was correlated with the location of the animal in a test environment [2,3] and that hippocampal damage causes spatial learning deficits [4]. The representation encoded by these *place*

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*cells* integrates the relationships among visual cues with kinesthetic self-motion information in order to recognize previously visited places and distinguish among perceptually similar places [5].

The amygdala system evaluates the innate or conditioned value of environmental cues. Context dependent conditioning is impaired by both hippocampus and amygdala lesions, but simple stimulus conditioning is impaired only by lesions of the amygdala [6]. Evidence suggesting a central role for the amygdala in discriminating the magnitude of reward comes from studies [7] in which rats with lesions of the central nucleus of the amygdala failed to discriminate between arms of a radial-maze that contained one or seven pieces of food. Lesions of the lateral amygdala made after the formation of cue-reward associations eliminated the conditioned preference [8] indicating that the lateral amygdala is also critical for the expression of value associations after they have been acquired.

The basal ganglia are a group of highly interconnected central brain structures that acts as action selection mechanism resolving conflicts between functional units that are in competition for behavioral expression [11,12]. Basal ganglia input occurs via a series of topographically organized, parallel processing streams [1] that encode the salience of potential actions. The action selection is done by maintaining or increasing inhibition on undesired actions and releasing inhibition from desired actions [9,10].

Computational models of each of these brain areas were integrated with sensory processing and motor execution modules to produce a navigation control system for a simulated robot rat. In order to facilitate flexible interaction between each module the BRAHMS framework [22] was used to handle the communication between the brain system models as well as the sensors and effectors of the simulated animal.

The performance of our hippocampus-amygdala-basal ganglia based navigation control system was tested by replicating a reinforcement based plus-maze learning task that has been used in a series of neurophysiological studies with rats [19,20,21]. Importantly, this plus maze task involves: 1. distinguishing between rewarded and non-rewarded locations based on visual cues; 2. place recognition based on the configuration of visual cues outside the plus-maze; 3. learning of specific place-value associations based on place specific reinforcement magnitudes; 4. selection of approach behaviors toward simultaneously available rewards whose relative, place-specific, magnitudes were learnt on previous trials.

## 2 System Architecture

The overall architecture of the navigation control system is shown in figure 1. There are two parallel processing streams. The stream going through the *dorsal* Basal Ganglia module processes inputs from touch (whiskers) and taste (battery recharge) sensors that elicit fixed stereotypical responses, i.e. collision avoidance reflexes and food ingestion. The stream going through the *ventral* Basal Ganglia module processes inputs from the visual and kinesthetic self-motion senses that guide goal-directed navigation.

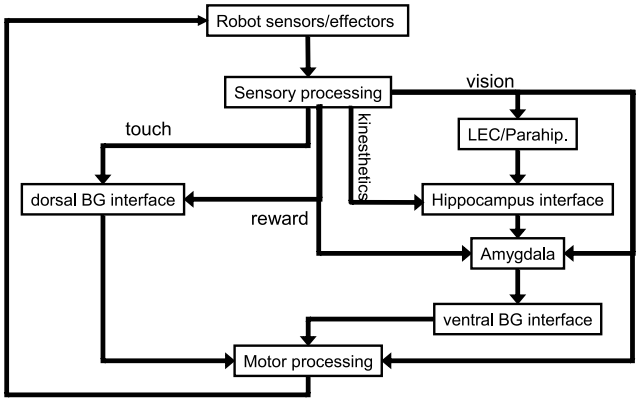


**Fig. 1.** Architecture of the navigation control system. The path through the *dorsal Basal Ganglia* controls fixed action patterns such as collision avoidance. The path through the *ventral Basal Ganglia* controls stimulus value dependent orienting responses.

### 2.1 Modules

**Robot Sensors/Effectors.** The simulated robot in our experiment is a wheeled rat-like robot (see figure 2 A). The robot effectors are its two independently driven wheels that allow it to move in the simulated environment. The sensory capabilities of the robot are:

**vision** provided by 2x160° color cameras place on the left and right side of the rat head giving a 320° visual field with a 40° blind area in the back (similar to a real rat [13]).

**touch** left and right whisker-like sensors for detecting left, right and frontal contact with the maze walls.

**kinesthetic self motion sense** provided by wheel motion sensors producing proprioception-like feedback of self motion.

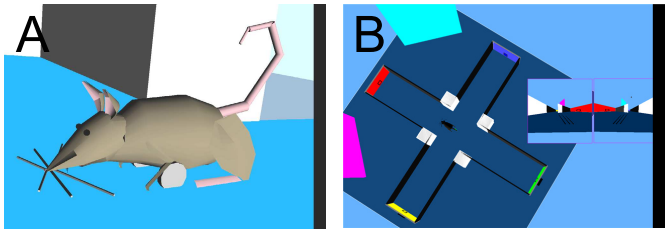


**Fig. 2.** Simulated wheeled rat-like robot (A) and plus-maze environment (B) used in our experiment

**kinesthetic orientation sense** implemented using a gyroscope based rotation sensor for measuring orientation changes, similar to the vestibular system in animals.

**reward detection** a voltmeter indicating the current charge in the robot battery. Since the "food" reward is simulated by a battery recharge this allows the robot to detect when and how much reward it receives.

**Sensory Processing.** The only biological constraint imposed on this module is that the outputs contain no information that would be impossible for a rat to have. One of the main tasks of the sensory processing module is to translate the modality specific sensory input signals into salience signals with a common normalized range of values across all modalities. The sensory processing produces the following outputs:

**vision:** In order to avoid complex issues of scene segmentation and object recognition all spatial landmarks and target locations were designated with unique colors (see figure 2 B). The visual processing simply detects the mean location and number of pixels of each color in the visual field. In the real rat experiments the stimuli at the goal locations all looked identical such that they were distinguishable only by the relative locations of external landmarks. The output from the visual processing therefore discarded all color information producing an unlabeled vector of egocentrically perceived object directions and a corresponding vector of visual object sizes. Only the perceived directions and sizes of the external landmarks and the maze center were labeled since these had clearly distinguishable shapes in the rat experiments.

**touch:** Input signals from the tactile sensors are converted into a three element vector signaling the salience of touch (degree of whisker deformation) at the left, right and front.

**kinesthetic senses:** The kinesthetic inputs concerning position and orientation changes are used to produce an estimate of current position relative to a starting reference by means of path integration. At the start of each simulated experiment the robot was placed at the center of the plus-maze with a random orientation. From there it visually located the two external landmarks and designated the direction between the landmarks as the 0° direction. Path integration is subsequently achieved by simply summing the orientation and position changes over time.

**reward detection:** The magnitude of reward that is received at any one time point (simulation iteration) is derived from the change in battery charge with respect to the previous time point.

**Parahippocampus.** The parahippocampus transforms egocentrically perceived object directions into self-orientation independent signals that can be used to recognize spatial locations based on the perceived spatial configuration of visible objects [14]. The output from parahippocampus is a vector specifying the visual angles between the external landmarks and each visual object in the maze.

**Hippocampus.** For spatial navigation tasks the primary function of the hippocampus is to map the environment and estimate current self-location. Spatial mapping relies on the inputs from the parahippocampus module concerning perceived spatial stimulus configurations and the current place estimate from path integration. The parahippocampal inputs are first compared against the previously mapped stimulus configurations. If no good match is found, a new *place cell* is created associating the inputs from parahippocampus with the path integration based place estimate. If however good match(es) are found, the hippocampal and path integration based place estimate are compared. If these place estimates are very different it is assumed that path integration has drifted due to accumulation of small errors and the place estimate is adjusted accordingly.

For goal directed navigation we hypothesize a second functional role for the hippocampus. Using the same place-stimulus associations that are generated during spatial mapping the hippocampus may be involved in distal place recognition. A possible neural substrate for this might be the spatial view cells that have been reported in primate hippocampus [15]. Even though the exact visual angles between the external landmarks and the objects inside the maze is specific to each maze location the gross distribution of the landmark positions with respect to the stimuli remains mostly invariant. For one stimulus light both landmarks are on the left, for another they are both on the right etc. We propose that it is these secondary place-stimulus association matches for distal locations that produce the inputs from the hippocampus to the amygdala.

**Amygdala.** The amygdala module provides association of values, i.e. salience of attraction or repulsion, with basics sensory stimuli or hippocampal place inputs. Stimulus/place-value associations are established whenever an innately rewarding/punishment related input is received. Any sensory input that is present at the time of the reward becomes associated with the rewarding input. For instance, when food is found near light, light becomes associated with food. At the same time an association is made between the current self-position estimate, from the hippocampus, and the food stimulus. The magnitude of the stimulus/place-value is determined by the strength of the association with the reward signal, which in turn is determined by the size of the reward that was received. The value associated with sensory stimuli/places is then assigned to the egocentric direction in which the stimuli/places are perceived.

**Dorsal/Ventral Basal Ganglia.** The dorsal and ventral basal ganglia modules are essentially the same. The only difference is the information that is processed in the modules and the type of behaviors they control.

In the dorsal module the basal ganglia channels represent *fixed action patterns* (FAPs). FAPs are species-specific, instinctive responses to specific patterns of stimulation [23]. A distinctive feature is that, once elicited, the overall form of the pattern is uninfluenced by further external cues [24]. The four FAPs in our navigating robot are: moving away from a wall on the right (1) on the left (2) or in front (3) and staying at the current location to consume food (4).

In the ventral module the basal ganglia channels represent *orienting responses*. In order to limit the number of necessary channels in the ventral module, the spatial directions are limited to eight equally spaced directions (forward, forward-right, right, backward-right, backward, backward-left, left and forward-left). All saliences assigned by the amygdala to directions within one of these eight sectors are pooled using the *max* operator.

The basal ganglia model used in these modules is an implementation of the model published in [16] which was previously applied in a robotic controller in [17,18]. The outputs of the basal ganglia are inhibitory in nature and function to suppress undesired actions [9]. Action selection therefore takes the form of selective dis-inhibition of the action that is coded by the channel with the most salient input, akin to an inverse winner-takes-all where the winner is the only channel that is not active.

In order to insure that the dorsal and ventral basal ganglia do not simultaneously disinhibit competing actions a high gain copy of the most salient signal to the dorsal pathway is used as an additional input to the ventral path. Thus, if there is a significant input for triggering a collision avoidance or reward collection behavior the navigation behavior is overridden.

**Motor Processing.** The motor processing module translates actions (as selected by the basal ganglia modules) into motor commands (left & right wheel velocities).

Since the dorsal path controls fixed action patterns a look-up table is used to execute these actions. If, for instance, the action to *move away from a wall on the left* is selected, the corresponding FAP is disinhibited in the look-up table causing a weak backward motion in the left wheel and a strong backward motion in the right wheel.

For orienting behaviors, selected by the ventral basal ganglia, each direction where an object is perceived (as signaled by the sensory processing module) produces a *potential movement command*. The ventral basal ganglia output inhibits all *potential movement commands* that are not in the selected direction sector. The visual salience weighted sum of the non-inhibited *potential movement commands* is used to determine the speeds of the left and right wheel motion.

Finally, if the basal ganglia modules produce no clear action selection (none or more than one action is disinhibited) right and left wheel velocities are set to zero and a *restlessness* level starts to build up. When restlessness reaches a pre-determined threshold, the robot performs a random left or right turn with some forward motion.

## 3 Simulator and Environment

The rat robot and plus maze environment were simulated using the Webots[1] robot simulation toolkit. The robot and environment are shown in figure 2. The

[1] Cyberbotics Ltd, www.cyberbotics.com

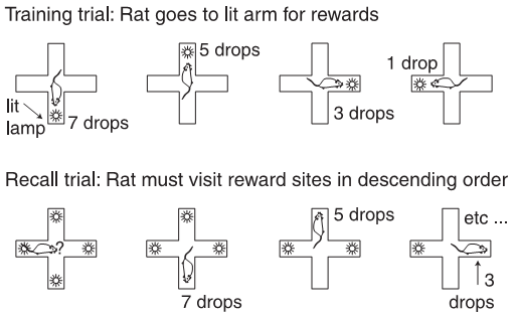


**Fig. 3.** The experimental task. First the robot performed a series of training trials where the correct choice was guided by the lit stimulus object light at the end of the appropriate maze arm. Each trial comprised a sequence of visits to the ends of the four maze arms providing battery "food" rewards with magnitude 7, 5, 3 and 1. During recall trials all object lights were lit, then were turned off one by one as the robot visited the reward locations at the end of the maze arms in the same order of descending reward value. (Adapted from Tabuchi et al., 2000).

colored panels at the end of the maze arm represent the stimulus object lights. When the robot touches the maze end walls the colored panel in that maze arm turns gray (i.e. the light is deactivated). A touch sensor in the floor of the maze center detects when the robot has returned to the center area and triggers the next phase of the task.

## 4 An Evaluation Task from Experimental Neurobiology

To test our rat brain inspired robot navigation system we used the *differentially rewarded plus-maze task* that was previously used by [19,20,21] in real rat experiments on the roles of amygdala, hippocampus and basal ganglia in spatial navigation. The basic task is illustrated in figure 3. The association between stimulus lights and reward was assumed to be pre-conditioned thus the Amygdala module was pre-coded with a strong value for lit objects. After reaching the end of a maze arm, and thus extinguishing the corresponding object light, the robot was motivated to return to the center of the maze since this was then the only lit object visible inside the maze. Upon reaching the maze center the light on the next arm was lit/no-longer occluded by the maze walls.

## 5 Results: Task Performance

A video of the simulated robot successfully performing the plus-maze task is available at `http://www.abrg.group.shef.ac.uk/people/ansgar/`. The simulation consisted of three stages corresponding to the pre-training, training and post-training sessions in the rat experiments:

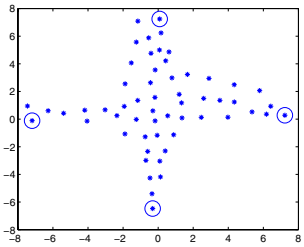


**Fig. 4.** Hippocampal place map of plus-maze learnt by the robot. Places encoded by the place cells are indicated with asterisks symbols. Places associated with values in the Amygdala are indicated with circles.

1. a pre-training test phase (3000 time steps) in which the stimuli are identical to the *recall trial* (figure 3, lower panel) but where the robot has had no prior exposure to the plus-maze and the only value association in amygdala is the pre-conditioned value for light cues. During this time the order in which the maze is explored is based simply on the orientation the robot happens to be facing at the start of the simulation. During this maze exposure the robot maps the plus-maze with its hippocampal place-cells.
2. a training phase (3500 time steps) during which the robot is guided down each maze arm in turn and given location specific amounts of reward when the end of an arm is reached. During this time the robot acquires the location specific object-value associations in the amygdala.
3. a post-training test phase (3750 time steps), or recall trial, during which the robot uses the learnt value associations to visit each plus maze arm in descending order of reward value.

The total duration of the simulation was 10250 time steps. The basal ganglia achieved clean action selection on 96.2% of occasions (390 time steps). During the pre-training test phase clear selection occured 94.5% of the time (164 time steps) while after training this was increased to 98.3% of the test phase duration (62 time steps).

During 37% of the pre-training period the action selections were closely fought (1111 time steps), i.e. the level of inhibition on the second most salience action was less than half the resting level inhibition. In the post-training period closely fought decisions occured only 22% of the time (818 time steps).

There were 1841 time steps during the total experiment where at least one of the external landmarks was occluded making visual place recognition impossible since visual place information is encoded as perceived angles between the external landmarks and the visual objects in the maze. During these time steps the amygdala is unable to associate the sensory stimuli with place specific values. In 78 instances this was correlated with indecision. In 498 instances the visual information was not relevant at that time since the robot was responding to a collision or feeding impulse with action selection being processed by the *dorsal* basal ganglia. For the other time steps during which a landmarks was occluded

action selection did not require the amygdala module since only one target object was visible to the robot a that time.

Figure 4 shows the hippocampal place map, illustrating the distribution of places coded by the place cells (asterisks symbols). Circles indicate the place cells that are associated with values in the amygdala.

## 6 Discussion

We have described a robot navigation control system based on the Hippocampus-Amygdala-Basal Ganglia circuit that plays a critical role in navigation and foraging behavior of rats. This controller selects between navigation goals based on spatial context defined values and guides the robot towards the selected goal.

As expected from previous implementations of Basal Ganglia models for robot control [18] our Basal Ganglia modules switch effectively between competing actions/targets depending on their relative salience.

The Hippocampus modules successfully integrated sensory information from visual and self-motion senses to establish a sense of self-location with respect to the surroundings and provide this place information as contextual cue for disambiguating visually identical stimuli.

The Amygdala module in turn used this contextual information to modulate the salience of sensory inputs thereby guiding the action selection in the Basal Ganglia toward the most highly rewarded stimulus. In addition to solving the plus-maze task this had the added benefit of reducing the number of instances of indecision by more than half.

In future we plan to use this model to test our understanding of these navigation related brain areas. In order to do this we will update the implementations of the Hippocampus and Amygdala modules to increase their neurophysiological accuracy in order to enable simulated electrophysiology and lesion studies.

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