Synthetic neural modeling applied to a real-world artifact

(brain networks/autonomous systems/neuronal group selection/learning/robotics)

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ABSTRACT   We describe the general design, operating principles, and performance of a neurally organized, multiply adaptive device (NOMAD) under control of a nervous system simulated in a computer. The complete system, Darwin IV, is the latest in a series of models based on the theory of neuronal group selection, which postulates that adaptive behavior is the result of selection in somatic time among synaptic populations. The simulated brain of Darwin IV includes visual and motor areas that are connected with NOMAD by telemetry. Under suitable conditions, Darwin IV can be trained to track a light moving in a random path. After such training, it can approach colored blocks and collect them to a home position. Following a series of contacts with such blocks, value signals received through a "snout" that senses conductivity allow it to sort these blocks on the basis of differences in color associated with differences in their conductivity. Darwin IV represents a new approach to synthetic neural modeling (SNM), a technique in which large-scale computer simulations are employed to analyze the interactions among the nervous system, the phenotype, and the environment of a designed organism as behavior develops. Darwin IV retains the advantages of SNM while avoiding the difficulties and pitfalls of attempting to simulate a rich environment in addition to a brain.

To analyze the relationships between complex brain structures and ongoing behavior is a daunting task. Even a full theoretical description of an animal's brain would not allow one easily to imagine its detailed workings in time and space. The multiple levels of control of brain function and the inherent variation and nonlinearity of brain anatomy and physiology frustrate mathematical analysis. For these reasons, we have adopted a different theoretical approach to understanding integrative brain function. This approach, synthetic neural modeling or SNM (1), correlates simultaneous large-scale computer simulations of the nervous system, the phenotype, and the changing environment of a designed organism in order to analyze interactions among all three as behavior develops. The success of this approach depends on adopting an explicit, well-founded theory of brain function. We have employed the theory of neuronal group selection (2–4), which proposes that brain function is based on (*i*) selectional events occurring among interacting cells to form neuroanatomy, (*ii*) further selectional events occurring among populations of synapses to enhance responses having adaptive value for the organism, and (*iii*) reentrant mappings mediated by massively parallel connections among functionally segregated brain areas. The theory claims that these means are sufficient to account for a variety of brain functions ranging from perception to motor responses.

The effectiveness of SNM has been examined in the so-called "Darwin" series of recognition automata (5), of which the most sophisticated was Darwin III. Darwin III

consisted of a simple sessile organism with a moveable eye and a four-jointed arm. It possessed neurons subserving contrast vision, light touch, kinesthesia, and motor outputs. A detailed set of neuroanatomical and neurochemical constraints was embedded within its structure, which was designed to embody a summation of evolutionary and developmental steps that might yield such a phenotype.

The environment of Darwin III consisted of objects of different shapes that appeared and moved across its visual field. These objects were chosen and driven by a random-number generator. A naive individual with its initial neural activity also driven by random-number generators was exposed to these stimuli. After such exposure, selection among its neuronal repertoires constrained by criteria of value (1, 5) resulted in consistent patterns of visual tracking, reaching with the arm, and discriminating among different objects.

The simplified and predesigned nature of the objects in the environment of Darwin III could have led, however, to inadvertent bias in the simulations, and the resulting limited behavior could not readily be compared with that of animals. For example, in most simulations, the visual input was presented at rather low resolution with carefully controlled noise content and a featureless background. The environment was two-dimensional, and the arm and the objects it manipulated were not subject to inertia or friction.

To avoid these limitations, we have extended SNM techniques to incorporate a real-world artifact in a new automaton, Darwin IV. This tactic restricts the computer simulation solely to the organization and dynamics of the nervous system; the environment and the artifact are real. The artifact itself, NOMAD (neurally organized, multiply adaptive device), moves about in the environment and communicates by telemetry with a simulated nervous system in a supercomputer. Darwin IV can execute built-in reflexes and several modes of behavior that are subject to selective amplification. These behavioral modes and reflexes are combined during experience to perform a number of exemplary tasks, some of which are described here.

MATERIALS AND METHODS

The Mobile Device. The mobile artifact called NOMAD was built to meet several design criteria. The device is small enough to move about effectively in a single experimental room but large enough for easy construction and adjustment. It is modular, permitting new sensor and effector elements affecting its "phenotype" to be added without major redesign. Wherever possible, it uses commercially available components.

NOMAD is based on a battery-powered mobile platform (RWI, Inc., Dublin, NH) with three steerable wheels that permit independent translational and rotational motion (Fig. 1, representation on left). Modules stacked on the platform

Abbreviations: NOMAD, neurally organized, multiply adaptive device; SNM, synthetic neural modeling.

provide effectors, sensors, and a telemetry interface to the nervous system, which is simulated on an nCUBE/10 parallel supercomputer (nCUBE, Beaverton, OR). A rigid "snout" fitted with an electromagnet permits NOMAD to grip small metal objects. NOMAD's primary visual input is provided by a miniature color CCD video camera (Toshiba IK-M30A) mounted near the top of the device. Camera azimuth can be varied by rotation of the platform as a whole; elevation can be directly controlled by NOMAD's nervous system. Additional "senses" are provided by electrical contacts in the snout (Fig. 1), which can detect the conductivity of objects gripped by the electromagnet ("taste"), and by IR proximity sensors (Banner SM312D) mounted around the periphery of the base. In current versions of NOMAD, the primary function of the IR sensors is to redirect the motion of the base when a collision with a large fixed object, such as a wall, is imminent.

A VME-bus 68020 computer (Oettle & Reichler Industrial Computers, Augsburg, F.R.G.) running the OS-9 real-time operating system (Microware Systems, Des Moines, IA)

provides interfaces linking the various sensors and effectors to the simulated nervous system. The on-board computer initiates no behavior by itself (other than manual override and collision avoidance) and is strictly under control of the nervous system simulated in the nCUBE.

The Environment. Experiments with NOMAD are carried out in a specially arranged room (Fig. 2 *Left*), equipped with a frame containing an 8 foot × 10 foot (1 foot = 0.305 m) raised floor (covered with either opaque or translucent plexiglass) and surrounded by "walls" consisting of projection screens. Depending on the studies to be carried out, the experimental area may be configured to include a collection of objects and can contain real or projected landmarks upon the floor or walls. The area under the raised floor contains a second mobile platform controlled by a conventional robotics program. This platform carries a flashlight which projects a stimulus upward through the translucent floor for tracking by NOMAD. A television camera mounted on the ceiling is used to record the behavior of NOMAD for later evaluation.

The Nervous System. A program based on biologically realistic neuronal networks was used to simulate and display
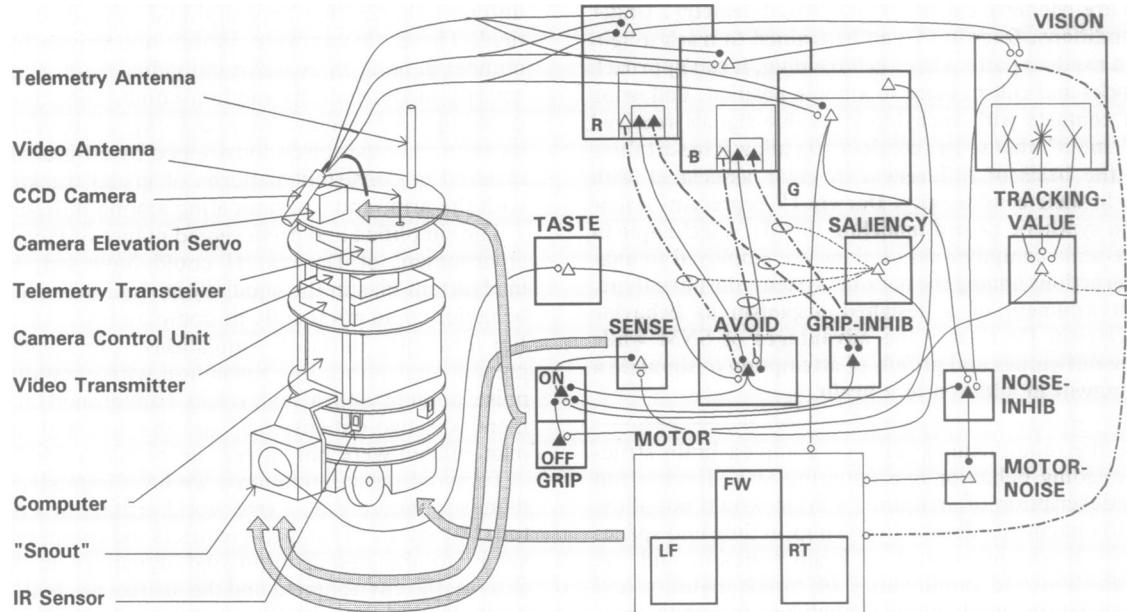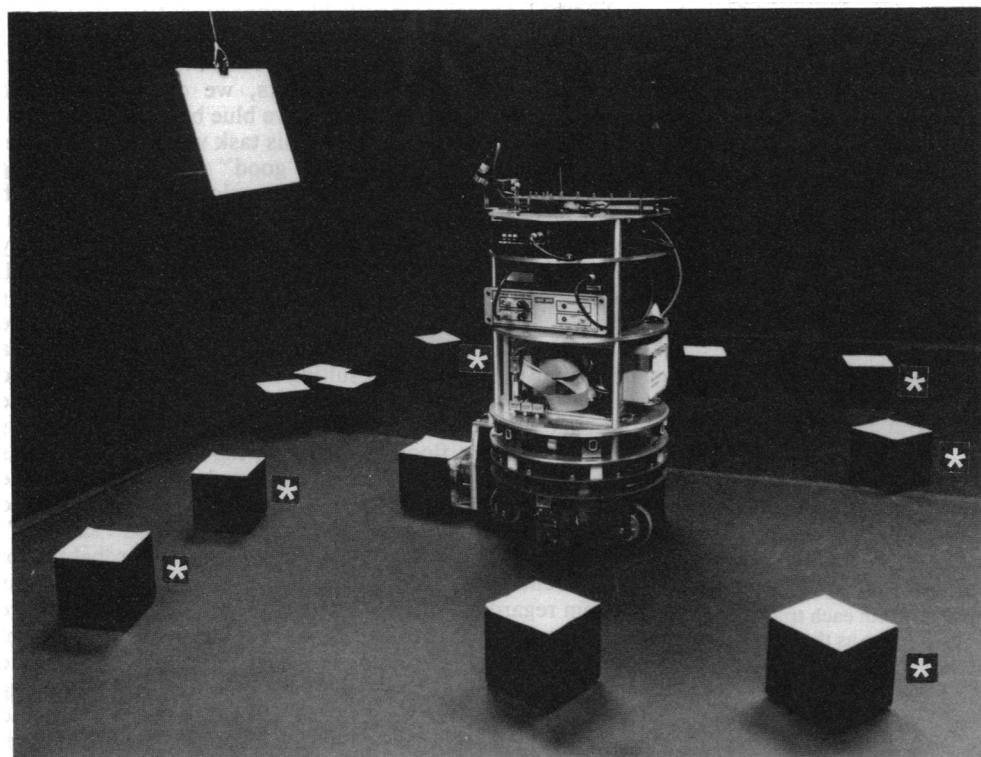
FIG. 1. Schematic diagram of Darwin IV showing the major components of the mobile artifact (representation on left) and the simulated nervous system used for the block sorting task (diagram on right). Boxes represent neuronal repertoires. Open and filled triangles denote excitatory and inhibitory cells, respectively. Lines connecting cells or repertoires indicate neuronal pathways (only a few representative cells and connections are shown); heavy arrows indicate efferent motor pathways leading to effectors. Open and filled circles indicate excitatory and inhibitory synapses, respectively. Synaptic pathways subject to value-dependent selective amplification are indicated by dot-dash lines (·—·—·). Dashed lines (- - - -) originating at the relevant value systems end in loops around the affected pathways. Beginning at the upper left, the red, blue, and green channels from the CCD video camera provide input to color-opposition cells in areas R, B, and G, respectively. Areas R and B jointly provide input to a VISION repertoire (top right), which directly excites MOTOR areas FW (for forward motion), LF (for left motion), and RT (for right motion), bottom center (see also Fig. 3 *Insets*). These areas in turn activate NOMAD's wheels to produce locomotion. MOTOR neurons also receive noise input from the MOTOR-NOISE area, which generates spontaneous (exploratory) motions of NOMAD. MOTOR-NOISE is inhibited by activity in NOISE-INHIB, which is excited by VISION, thereby reducing spontaneous locomotion when a potential tracking target is in sight. Connections from VISION to MOTOR are amplified under the selective influence of the TRACKING-VALUE repertoire. TRACKING-VALUE responds most strongly to light falling directly in front of NOMAD, which excites the rectangular area near the bottom of the VISION repertoire, corresponding to the proximal region of the field of view (trapezoidal area in Fig. 2 *Right*). Cells in the foveal and perifoveal regions of R and B (smaller rectangles at the bottoms of R and B repertoires) are also connected via selectively modified synapses (see below) to excite the area AVOID and to inhibit the area GRIP-INHIB when an object is sighted at a moderate distance. After training, these areas are responsible, respectively, for initiating the avoidance and preventing the gripping reflexes discussed in the text. GRIP-INHIB is normally active, leading to inhibition of GRIP. When GRIP-INHIB is itself inhibited, GRIP is released from inhibition and can activate the snout magnet and camera elevation effectors, but only when excitatory input is received at the same time from TRACKING-VALUE, causing NOMAD to pick up objects that have been foveated. AVOID acts by inhibiting both NOISE-INHIB and GRIP, causing NOMAD to move randomly without activating its gripping magnet. The green (G) visual repertoire is responsible for recognition of the green home area. When the camera has been elevated and the green target is seen from a distance (when cells at the bottom of G are active), MOTOR and NOISE-INHIB are excited, causing NOMAD to move towards the green target. When the target is reached, other cells (top of G) become active, exciting GRIP-OFF cells and providing the SALIENCY signal. SALIENCY immediately excites SENSE neurons, activating the conductivity sense in the snout. "Bad taste" activates TASTE cells, which excite reflex avoidance via a direct pathway to AVOID. Activation of AVOID by this mechanism while SALIENCY is still active leads to strengthening of connections from R or B (whichever was active when the object was recently viewed) to AVOID; as a consequence, after training, avoidance can be activated directly by visual signals without need for the object to be tasted.

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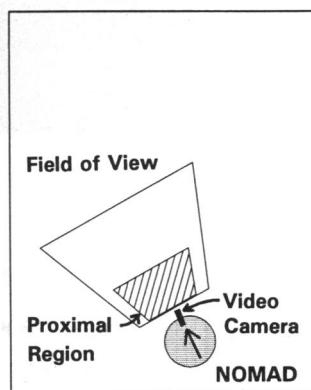
FIG. 2. (*Left*) Photograph of NOMAD in its environment as arranged for the block-sorting experiments (showing NOMAD, randomly distributed blocks, and the landmark for "home position"). Blue blocks are labeled with an asterisk. (*Right*) Schematic view of NOMAD (stippled), its environment, and its field of view. The hatched region indicates the proximal part of the visual field.

the nervous system of Darwin IV (Fig. 1, diagram on right) and to collect performance data. The previous network specifications for Darwin III (1, 5) served as a prototype for the development of the new networks that were required to extend the simulation to real-world sensors and effectors. A topographically mapped visual network receives input from the three color channels of the video camera and projects to three groups of motoneurons, one each for translation, for rotation to the left, and for rotation to the right (Fig. 1). Other networks handle sensory and motor pathways pertaining to the snout.

Neuronal responses are updated in discrete time steps by use of rules for cellular activity and synaptic modification based on those employed in Darwin III (1, 5). Visual units cease to respond to stationary visual images as a result of simulated cellular depression. Synaptic modification depends not only on pre- and postsynaptic activity but also on the activity of a set of neuronal units (a value system, see ref. 1) reflecting the adaptive value of NOMAD's recent behavior. Such value systems embed structural features of particular nervous systems and phenotypes selected during evolution (1, 5). They provide broad constraints for possible adaptive behaviors but, in general, do not fully determine the specific behaviors or categorizations of the individual organism. Darwin IV contains two distinct value systems. The first is implemented by visual units that respond more strongly when a target appears in the region of the visual field adjacent to NOMAD's snout. Its activity influences the probability of changes in synaptic strength between visual and motor networks leading to tracking (Fig. 1, diagram on right). The second value system, referred to as "saliency," is triggered whenever Darwin IV activates its snout sensor to assess surface conductivity. "Saliency" modulates changes in the strength of the connections linking visual repertoires with reflex centers (Fig. 1). The actions of neural repertoires controlling Darwin IV's built-in reflexes are described in detail in *Results*.

RESULTS

Tracking. As a first example of a simple behavior, we investigated the ability of Darwin IV to approach and track a moving light mounted on the mobile base below the translucent floor of the environment. NOMAD's video camera was installed at the front of the device pointing at an angle of roughly 45 degrees down from the horizontal. Fig. 2 *Right* illustrates the relative sizes of the environment, NOMAD, and the field of view of NOMAD's camera, which covers 14% of the entire environment under unobstructed conditions. Note that the oblique angle of the camera gives rise to keystone distortion of the visual image and that distant stimuli appear to grow larger when approached.

Darwin IV's motor system includes separate repertoires of units that are spontaneously active. In the absence of a visual stimulus, NOMAD rotates and translates at random, driven by this spontaneous activity (search mode). When a stimulus appears and motoneurons are directly activated by the visual network (tracking mode), spontaneous activity is inhibited by separate connections from the visual area. After a movement has occurred, the synaptic populations giving rise to this movement are probabilistically strengthened or weakened by selection (see Fig. 3 *Insets*) depending on whether or not the movement resulted in an increase in value. After some time, those movements that facilitate close approaches and tracking occur more frequently than others. During training, selective modification of synaptic strengths automatically accommodates to any nonlinearities resulting from the distorted visual image and from the mechanics of NOMAD's motor apparatus.

During early trials, NOMAD rarely approaches the light (Fig. 3). Even if NOMAD approaches the light by chance, it is unable to track the target's movements because there is no innate adaptation to carry out this task. After experience and the concomitant selectional events in the nervous system, NOMAD tracks the light along complicated trajectories (Fig. 3), losing contact only occasionally. When contact is lost, NOMAD briefly reverts to search mode, but it resumes tracking after encountering the light again.

Sorting. After successful training for the tracking task, we used the networks developed by Darwin IV while tracking a moving light for a different but related task: locating and approaching stationary objects. Following exposure to the
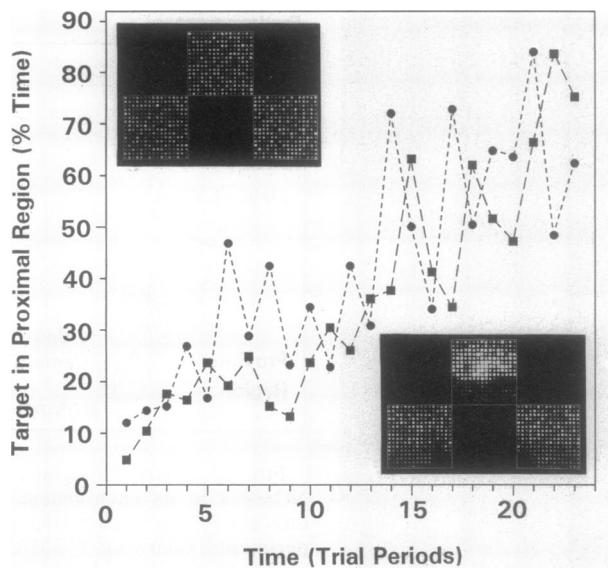
FIG. 3. Training curve for two individual runs of Darwin IV's tracking system. Time is given in trial periods, with each trial period lasting for 250 time steps. The success rate is given as the percent of total time that the target was in the proximal part of NOMAD's visual field (see Fig. 2 *Right*). (*Insets*) Strengths of connections between VISION and MOTOR repertoires before (*Upper Left*) and after (*Lower Right*) training. Stronger connections are indicated by larger and lighter squares.

tracking task, NOMAD was placed on an opaque floor under room-light illumination. The environment contained colored blocks (hollow 10-cm cubes) made of 0.008-inch gauge sheet steel (Fig. 2 *Left*). Surfaces of the blocks were coated with translucent plastic sheets of two kinds, one of which was electrically conductive (Southwall Technologies, Palo Alto, CA), while the other was not. The conductivity of each block was associated arbitrarily with its color—in the experiments reported here, conductive blocks were blue, and nonconductive blocks were red. We distributed the blocks in various patterns without providing any information to Darwin IV on their order or position or on the correlation of conductivity with color. In one part of the environment (see Fig. 2 *Left*), a raised green landmark signaled the "home position," a potential collection point for colored blocks.

To permit the device to distinguish between different colored blocks, the camera input was transmitted to three visual maps, each sensitive to a different primary color (red, green, or blue) and topographically mapped to the tracking vision network (Fig. 1). Four motor reflex networks were also used. One, the "gripping reflex," turns the snout magnet on whenever an object appears in its immediate vicinity. Prior to training, this network is activated with a probability of around 50%, and as a result the device picks up blocks randomly with this frequency. Value-dependent modification of connections from the red and blue color networks can modify this probability. A second reflex network controls the elevation of the camera. Two elevations were used in the sorting experiment: one pointing 45° down from the horizon for searching for blocks, the other pointing horizontally for searching for the "home position." Normally the camera is positioned to search for blocks, but it is automatically elevated when the snout magnet is turned on and released when it is turned off. A third reflex is triggered whenever the green landmark activates the upper portion of the visual field (signaling proximity to home); NOMAD stops, the camera returns to face downward, and conductivity receptors in the snout are activated. The fourth reflex network strongly activates the repertoire generating spontaneous locomotion if a conductive block ("bad taste") is sensed via the snout, resulting in an avoidance response. This

network also receives modifiable connections from the red and blue color networks.

To test the global behavior of Darwin IV in searching for, locating, and approaching objects, we devised a simple block-sorting task using conductive blue blocks and nonconductive red blocks. The aim of this task was to train Darwin IV, through experience with "good" and "bad" tasting blocks, to avoid the blocks whose color is associated with "bad taste" without the need to approach and grip them. Before training, NOMAD approached all blocks in its vicinity under the guidance of its tracking system and, in ≈50% of all approaches, established physical contact with the block's surface. In these cases, the block was gripped with the magnetic snout, and the camera was raised by reflex into a horizontal position. The resulting change in Darwin IV's field of view allowed it to use the tracking system to search for the designated home position while pushing the block with its snout across the floor. As soon as the home position was reached, the camera turned downward again towards the block and the conductive properties of the block were sensed with the snout, leading to a strong signal in the "saliency" value system (Fig. 1). This signal increases the probability of concurrent synaptic changes within Darwin IV's nervous system regardless of whether the block is in fact conductive or nonconductive. In general, the result is a strengthening of the association between the active vision repertoires and the gripping reflex. As a consequence, the probability of gripping an object in the future increases. If high conductivity ("bad taste") is sensed, however, the avoidance reflex is activated; this causes NOMAD to turn away from the direction of the object. Value thus allows an association to be formed between the color of the object in the foveal region and an aversive response. Because of resulting changes in synaptic strengths, in future encounters the appearance in the perifoveal region of an object of the color previously sensed as having bad taste is sufficient to trigger an avoidance response. After having delivered an object of either color to the home position, NOMAD resumes its search for new objects.

Results are shown in Table 1. If snout sensing and the corresponding value network are disabled, NOMAD collects red and blue blocks but does not behaviorally discriminate according to their color. If the value network is enabled, after a few encounters with red and blue blocks NOMAD sorts them according to color: only red blocks are taken to the home position, and blue blocks are actively avoided.

DISCUSSION

The experiments described in this paper were deliberately limited to very simple tasks. Our main objective was to

Table 1. Response frequencies in the block-sorting task

	Color	Contact	Grip	Home	Avoid
"Block collection"	Red	24	15	11	0
(Value disabled)	Blue	34	16	13	0
"Block sorting"	Red	30	30	21	0
(Value enabled)	Blue	0	0	0	32

Data were collected from five test sessions while value was disabled and five test sessions while value was enabled; each test session lasted 150 time steps. At the beginning of a session, 14 colored blocks (7 red and 7 blue) were distributed at random over the environmental platform, and NOMAD began its search from the edge of one side of the platform. Color, color of blocks to which data refer; Contact, number of times NOMAD established physical contact with a block; Grip, number of times NOMAD gripped the encountered block with its magnet; Home, number of times NOMAD reached the home position with a block attached to its snout; Avoid, number of times NOMAD actively avoided a blue block that came into view. The difference between Grip and Home results from accidental losses of blocks due to collisions with other blocks in the environment.

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demonstrate the feasibility of extending SNM (1, 5) to an artifact capable of performance in the real world. We found that it is possible to conduct long-lasting runs and to record neural and behavioral data continuously. These data can be used for the analysis of cross-level interactions among synaptic changes, environmental stimuli, phenotypic variations, and behavior.

Darwin IV's behavioral repertoire includes several reflex responses (gripping, camera elevation, snout sensing, and avoidance) as well as adaptive behaviors resulting from sensorimotor interactions (such as tracking, approaching, and homing). In general, adaptive behaviors depend upon experience and are not predictable in detail, although they follow constraints posed by value schemes. Some of Darwin IV's tasks, for example block sorting, require the successful combination, based on experience, of sequences of reflex and adaptive behaviors. Within bounds, the device also shows some degree of opportunism, being able to transfer "learned" behaviors (such as approaching and tracking) to different environmental situations. For example, after training it was possible to use the same networks for tracking a moving light and for approaching stationary colored blocks or a colored home position on the basis of the differential reflectance of all three stimuli relative to the background.

An important constraint in determining NOMAD's tracking performance is set by the relative speeds of NOMAD and the stimulus. Such constraints on the speed of the stimulus can be analyzed by considering training as a form of a random walk over synaptic connections. With each step, the connections become either more appropriate for tracking or less appropriate, with probabilities that depend on the maximum distance moved by the device and the stimulus. In the context of the "ruin problem" of random walk theory (6), it can be shown that if the maximum distances traveled per time step by the device and by the stimulus are the same, the probability that the device will successfully learn to track is only 0.5. A decrease in the speed of the stimulus by only 5% (to 95% of that of the device) results, however, in a dramatic increase in the probability of successful learning to 0.96. This analysis suggests that if the stimulus moves just slightly slower than NOMAD itself, successful training becomes a robust phenomenon. Such a relationship has indeed been observed and tested in our experiments. We conclude that plausible and realistic constraints on critical phenotypic parameters can lead to a high probability for adaptive behavior despite the absence of an explicit program specifying behavior in detail.

Others working more directly in the field of robotics have attempted to design mobile devices operating in a real-world environment (for review, see ref. 7). Despite much effort, however, "classical" artificial intelligence programs have generally been unable to deal effectively with a rich environment (8). More recent work (9–13) on real or simulated behaving robots has emphasized how systems composed of independent modules can give rise to composite behaviors in the absence of centralized control. Unlike Darwin IV, the design used for many of these systems is based on invertebrates, is hard-wired and nonplastic, and minimizes direct interactions between the constituent modules.

While the simple behaviors we have modeled so far using Darwin IV bear certain resemblances to these systems, our approach differs in several fundamental respects. Unlike that of other systems, Darwin IV's behavioral repertoire consists of a combination of several built-in reflexes with various modes of ongoing adaptive behaviors emerging from the encounters of a selectionally based nervous system with an environment. Most of the elementary behaviors are subject to value-dependent modification of synapses. Sensor-driven modes depend directly on selective synaptic processes to mold the resulting behavioral patterns. As a consequence of selective synaptic change, the elementary behaviors combine with each other and with reflexes to yield associative sequences that allow sorting of objects in the absence of a fixed sequence of programmed instructions. Each behavior is controlled by multiple repertoires in the nervous system; a strict one-to-one mapping does not exist between neural centers and the behaviors elicited by their activation.

The problem of understanding how adaptive action in a rich environment is initiated and controlled by vertebrate nervous systems requires the development and testing of global models of brain function. SNM is aimed at realistic modeling of such nervous systems, and as such it uses biologically based synaptic rules to modify ongoing behavior. NOMAD, as embedded within the Darwin IV simulation, provides a valuable testing ground for neural models in real-world environments. It allows the investigator to explore many possible combinations of phenotypic structure and neuronal architecture. Specifically, it allows modeling of both modular ("invertebrate-like") and cortically integrated ("higher") nervous systems. The present preliminary studies provide a basis for incorporating increasingly complex neuronal structures into the simulation and for evaluating the impact of their function on behavior.

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