How accurate need sensory coding be for behaviour? Experiments using a mobile robot

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Abstract

This paper argues that for those neuronal systems which control behaviour, reliable responses are more appropriate than precise responses. We illustrate this argument using a mobile robot controlled by the responses of a neuronal model of the locust LGMD system, a visual system which responds to looming objects. Our experiments show that although the responses of the model LGMD vary widely as the robot approaches obstacles, they still trigger avoidance responses. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Survival is a fundamental goal of every animal. The neuronal systems which control those behaviours necessary for survival must be as reliable as possible to maximize the animal's chances. However, reliable in this context does not necessarily mean precise. For an animal to avoid collisions or evade a predator, it is most important for it to trigger the appropriate behaviour in good time, not necessarily at the optimum time. Precision on the time scale of milliseconds is useless if the relevant behaviour is triggered only 50% of the time.

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When the neuronal systems which control behaviours are studied using simplified stimuli, the responses of these systems, and the timing of the behaviours they control, often correlate with particular stimulus features. For example, in a flying locust, obstacle avoidance behaviours are triggered when the angle subtended by a looming object exceeds a certain threshold [10]. However, these stimuli generally do not capture the variety of stimuli the animal experiences in its natural environment. In these more complex stimuli, features of individual objects are harder to detect and the key features to which sensory systems respond more difficult to identify [6]. Thus, for reliable control of behaviour a more robust strategy has to be adopted, where temporal precision is compromised in order to enhance reliability.

Here we present a qualitative study which illustrates that collision avoidance behaviour can be controlled reliably using imprecise neuronal responses. Our model system was the lobula giant movement detector (LGMD) of the locust, a wide-field visual interneuron which responds selectivity to objects approaching on a collision course [9,3]. These responses are transmitted rapidly to motor areas (via the postsynaptic descending contralateral movement detector (DCMD), an interneuron which matches LGMD spikes one-for-one [5,7]), suggesting that the LGMD plays a role in triggering avoidance responses. In our experiments, the LGMD responses were used to control the behaviour of a small mobile robot: as the robot explored its arena, the LGMD triggered avoidance reactions when the robot approached obstacles.

2. Methods

We implemented a model of the LGMD, which captures the basic anatomical and physiological properties of the LGMD and its input organization [8], using the simulation software IQR421 [11]. The input to the model LGMD was provided by a wide-angle (78° horizontal, 57° vertical) monochrome camera mounted on a Khepera miniature mobile robot (K-Team AG, Lausanne, Switzerland). The movement of the robot was controlled by a second neuronal circuit which produced forward motion unless the responses of the LGMD triggered avoidance behaviour (see below). An overhead camera was used to track the movements of the robot. Fig. 1 summarizes this system, which operated in real-time (25 updates/s). For a full description of the model and the experimental system, see [1].

The robot moved within an arena comprising large Duplo blocks of several colours surrounded by a white wall. The colours of the blocks produced a range of contrasts within the scene, and both the lighting within the laboratory and the behaviour of the robot provided a wider variation of stimuli for the LGMD than those used in previous physiological experiments (Fig. 2).

The responses of the LGMD model were integrated using a leaky integrate-and-fire neuron in the robot control circuit, and avoidance reactions were triggered when the activity in this neuron exceeded a predefined threshold. The time constant of this neuron was short when compared with the time taken for the robot to cross the arena. The avoidance reaction triggered was an anti-clockwise rotation of fixed duration,
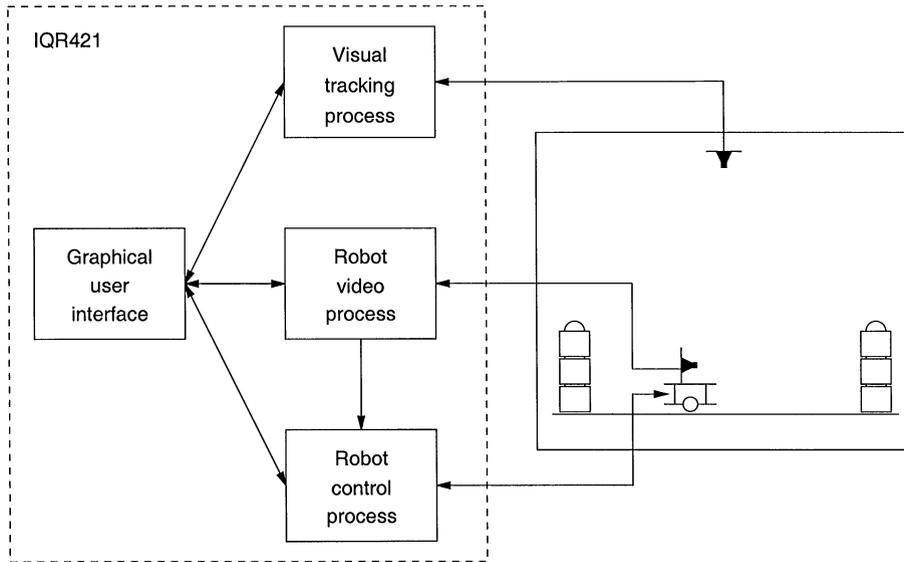
Fig. 1. Schematic representation of the experimental system, showing the input/output devices used and the flow of information within IQR421. The camera image from the robot stimulated a neuronal model of the LGMD within the robot vision process, and the responses of LGMD used to trigger avoidance reactions via the robot control process. An overhead camera was used to track the robot's position.
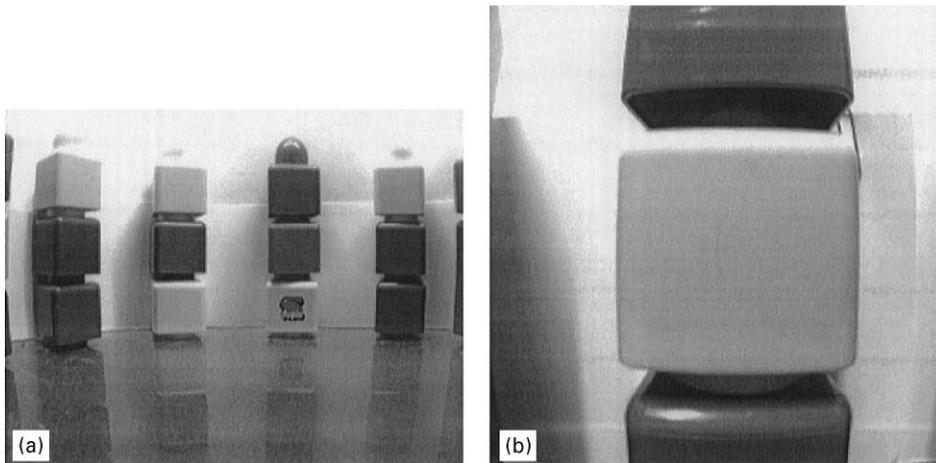
Fig. 2. View from the robot. (a) Across the arena (30 cm away from the blocks). The field-of-view of the camera captures several objects. (b) 5 cm from a block, when only a single object can be seen.

after which the robot resumed forward motion; the position of the robot relative to the blocks was not taken into account before triggering a turn.

Experiments were conducted over a range of speeds of forward motion. The parameters of the model were constant for all speeds.

3. Results

We first studied the responses of the robot with the avoidance reactions disabled, in order to observe the responses of the model LGMD prior to collision. As shown in Fig. 3, the average spike frequency of the LGMD responses changed unpredictably during approach, and the standard deviation of responses was large. The variability of these responses prevents the observation of any precise mapping between the LGMD responses and stimulus features.

In our second experiment, we enabled the LGMD-triggered obstacle avoidance behaviour. Example results are shown in Fig. 4, which illustrates the trajectory followed by the robot. In spite of the imprecise nature of the LGMD responses highlighted above, the robot was able to avoid collisions using only the LGMD responses as its cue. Note that the distance of the robot from the blocks when the course changed (due to the anticlockwise avoidance reaction) was not constant: several reactions occurred while the robot was close to the centre of the arena, but others occurred much closer to the edge.

4. Discussion

Our experiments show that the responses of the model LGMD as the robot approaches obstacles vary widely, but can still be used to correctly trigger avoidance responses. The variability in the LGMD responses reflects the wide range of stimuli generated by the movement of the robot around the arena. Frequently, the view of the robot included two or more blocks, and the response produced by each block was dependent upon its colour. Such variability has not been widely used in studies of the LGMD and similar sensory systems, but it represents more closely the variability of stimuli which the animal encounters in its natural environment. In that environment, individual obstacles may be difficult to distinguish from the background and other objects.

The need to respond successfully in real-world visual environments suggests that the locust must use the responses of the LGMD in a conservative avoidance strategy, in which precise timing is reduced in order to increase the chances of success. It has been suggested that the precise timing of a peak in the spike rate of the LGMD, which encodes a particular angular subtense of the stimulus on the eye, correlates with the flexion of the hind leg of the locust, an action which prepares the animal to trigger an escape jump [2, note 15]. However, such precision may result from the simplistic stimuli used in the study: in a complex visual environment, the observed peak is much less likely to occur with such precision due to the difficulty of encoding specific features in natural scenes.
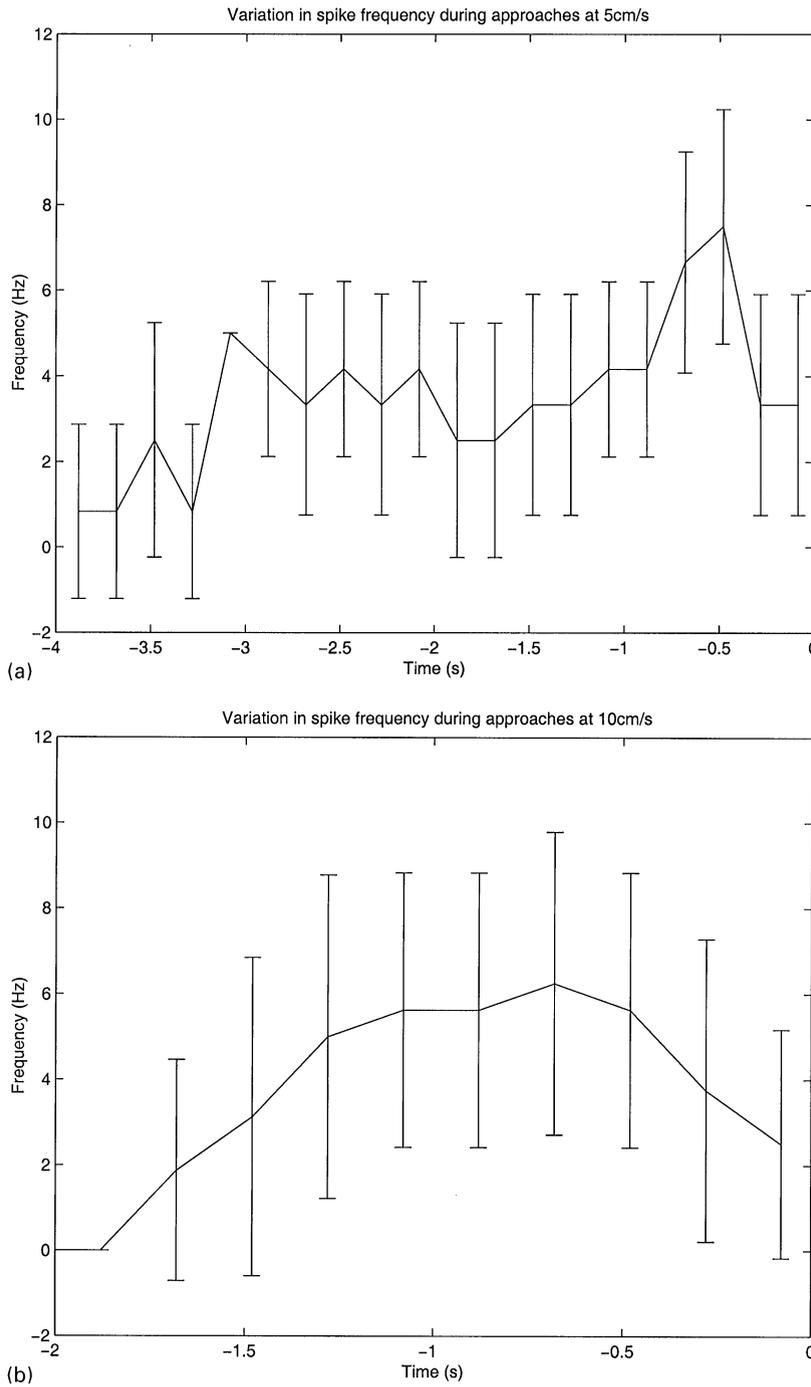
Fig. 3. Average spike frequency of the LGMD. The speed of the robot was (a) 5 cm/s and (b) 10 cm/s. Error bars show standard deviation.
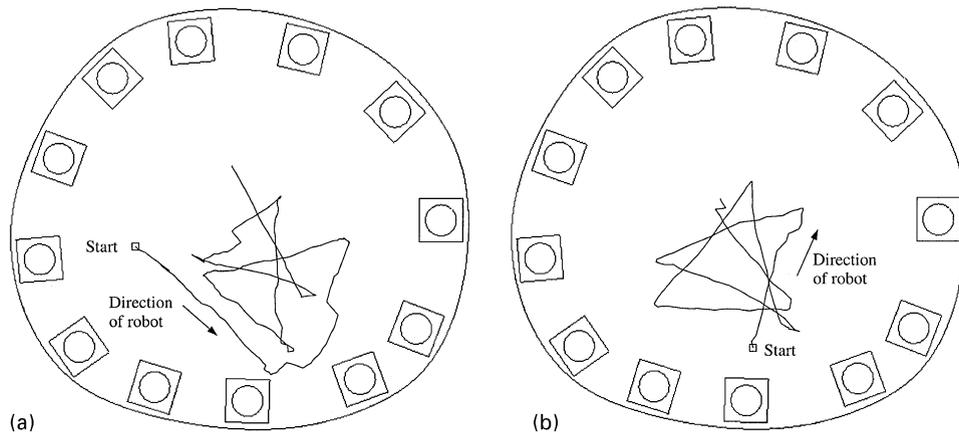
Fig. 4. Trajectory of the robot when LGMD responses were used to trigger avoidance reactions. The speed of the robot was (a) 5 cm/s, (b) 10 cm/s. Note the variation in distance between the robot and the blocks when avoidance reactions (anticlockwise turns) were triggered.

Of course, some animal behaviours are triggered with exceptional precision. The wing-folding behaviour seen as gannets dive for food occurs precisely during successive dives [4]. In this case, however, such precision is essential: the bird must compromise between the risk of injury to its wings as it enters the water at high speed and maintaining control during the dive. In this case, the neuronal mechanisms mediating the behaviour, which was observed in animals in their natural environment, will reflect this precision.

In conclusion, we have shown that reliable behaviour can be controlled using imprecise neuronal responses. The choice of behavioural strategy represents a compromise between reliability and precision.

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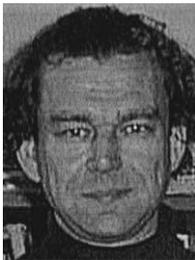
Paul F.M.J. Verschure, born 1962, is a group leader at the Institute of Neuroinformatics, ETH-University Zurich, Switzerland. He received both his M.A. and Ph.D. in psychology. His scientific aim is to find a grounding for psychological explanations in neuroscience through the use of synthetic methods. He has pursued his research working at different institutes in the US (Neurosciences Institute and The Salk Institute, both in San Diego) and Europe (University of Amsterdam and University of Zurich). He works on biologically realistic models of perception, learning, and problem solving which are applied to robots and on the software tools which support this research in synthetic epistemology, IQR421. His work has made significant contributions to the developing field of, so-called, new artificial intelligence. In addition, he applies these models in the domain of art and technology.