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Editorial

Computational and biological perspectives on the problem of navigation

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The question of how mobile and intelligent agents navigate in an uncertain and unstable world is one of the most interesting intellectual questions of today, attracting researchers from a wide range of disciplines, including those interested in understanding natural cognition and those interested in emulating it. This *Connection Science* special issue on navigation, which brings together scientists working on biological and artificial navigation, was conceived in the hope that communication between disciplines could generate new ideas on all sides.

Cross-talk between engineers, computer scientists and biologists is often difficult to establish because of the different languages and different ways of thinking that each group uses. Furthermore, solutions to problems are often more constrained by the medium in which they occur than by their computational nature of the problem. Just as aeroplane engineers did not find it necessary to emulate feathers and flapping of wings to achieve artificial flight, so the roboticists of today often eschew biological solutions to problems because biological systems are slow and they use clumsy, energetically expensive and space-consuming processing elements, while electronic systems are immensely fast and compact. Nevertheless, no artificial system has yet come close to replicating the superlative abilities of biological cognition, so there may be much for designers of artificial systems to learn from studying biological ones: cognition is a lot more complicated than flight. Conversely, biologists can look to engineering and computer science to find descriptions of their problems in computational terms, and gain an understanding of a biological competence that would have been hard to gain from simply studying their model animal in isolation (Webb 2000).

With this in mind, we tried to attract a mix of biological and computational papers that speak to the issue of navigation in a way that could be mutually illuminating. This has been very successful, with an eclectic mix of papers evenly spread between computational/engineering and biological authors. The issue begins in the biological domain with a general discussion by Cheng of a problem that has been vexing navigational biologists for a number of years now: namely, the degree to which animals rely on the geometry of the environment, rather than specific cues within it, to navigate. Cheng is ideally placed to review this debate since it arose

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from his own surprising and counterintuitive observation, in 1986, that rats preferred to use the geometry of the environment to help them locate a goal, even though the cues provided by the geometry were more ambiguous than those provided by specific features (Cheng 1986). This finding led to the proposal that geometric processing comprises a 'module' within the vertebrate navigational system, such that when animals navigate they preferentially use geometry, and this geometric representation is relatively impervious to non-geometric information. Cheng now re-examines this hypothesis in light of recent data. The issue is interesting because it relates not only to the kinds of information that animals use in spatial processing, but also to the modularity (or otherwise) of their processing: both issues deserve consideration by designers of artificial cognitive systems.

The next two papers consider the use of motion information by agents that navigate. This is an issue that has been exercising biologists for some time because of the growing evidence that animals use motion information on an almost continuous basis in order to perform path integration (constant updating of position with respect to home: see below). The two papers here concern themselves with optic flow and the way in which it might be possible to extract information from optic flow that could be used to construct a map (in the case of the first paper) or return to a home base (in the case of the second paper). In the first paper, Ohnishi and Imiya develop an algorithm that allows a mobile robot to detect optic flow from a sequence of camera images, and from there to compute the locations of obstacles and the relative position and motion of the robot. This promises to be an interesting technique for allowing robots to perform simple obstacle avoidance for relatively little computational cost, and it suggests that even more complex map-based navigation might be possible without the need for landmark recognition or geometric computation. This proposal will also be of interest to biologists, whose models tend to assume that complex sensory processing must precede navigational computations.

The next paper, by Vardy and Möller, is also concerned with optic flow and it turns to the issue of homing, an issue that is then also taken up by biologists in the subsequent three papers. Homing is one of the simplest and most important kinds of navigation because it returns the agent not only to the start point of its journey, but also to a place of presumed familiarity and safety. It needs to be very fast, as one would expect of a mechanism designed to get an animal home to safety as quickly as possible, and it would thus be adaptive to keep navigational computations to a minimum. Again, optic flow seems to be a good means of achieving this, and Vardy and Möller propose a method by which optic flow can be used to achieve 'block matching' (comparison of visual scenes from current location and home) that enables homing. This technique looks to be both a plausible model of insect homing and a potentially useful technique in robotics.

Moving from insects and robots to birds, the next paper, by Wallraff, discusses the question of how homing pigeons home: a remarkable capability that has remained incompletely explained for many years. Wallraff considers, and rejects, a number of plausible candidate homing mechanisms, such as path integration (see below), which is known to contribute to short-range navigation in a number of species. He considers the issue of gradient detection and argues that the evidence to date favours the idea that pigeons can detect the gradients of aromatic hydrocarbons and use these to compute the homeward direction. When closer to home, in familiar territory, they switch to using visual cues, which are more precise and allow more tightly focused navigation towards the nest. Use of gradients is an interesting possibility as it suggests a reasonably sophisticated navigational capability occurring without the need for explicit representation of metric information.

The next two papers look at homing in rats, whose ecological circumstances are quite different from pigeons but which nevertheless are very good at homing, at least over short distances. The fast and direct nature of rodent homing has suggested to many biologists that the animal probably knows which way home is at any point along its outward journey, and this has been supported by a wealth of studies (see Etienne and Jeffery (2004) for review) that covert displacement of an animal causes it to 'home' in a direction that would return it to the nest if it had not been so displaced, thus ruling out any kind of navigation relying on cues emanating from the home, or using local cues such as landmarks. It is now assumed by most biologists that homing generally makes use of the capacity of most animals to *path integrate*: that is, to keep track of their movements as they make their outwards journey so that they are constantly availed of the distance and direction back home.

A critical component of path integration is the capacity to maintain a constant representation of directional heading – the so-called 'sense of direction'. Dudchenko and Bruce have examined whether rats can use their sense of direction to return to a home box on a circular maze. Slow rotation of rats at a rate below the vestibular detection threshold causes a rotation of the neural place representation (Jeffery *et al.* 1997), suggesting that the sense of direction, at least at a neural level, is also rotated by this manipulation. Dudchenko and Bruce asked: Can such rotation rotate the animal's navigational decisions too? In other words, does the behaviour of the neural place system mirror that of the animals as a whole? And, do animals rely on path integration to remain oriented when visual orienting cues are unavailable? These are important questions, made more complicated by the propensity of animals to use a mixture of information sources and switch between these with apparent ease: something that roboticists have been considering when trying to compensate for inadequate or intermittent sensory inputs.

In the final homing paper of the set, Martin *et al.* explored whether rats can learn to return to the starting point of their journey if this was not a fixed point, but instead varied from trial to trial. This variation from trial to trial causes the task to become a working memory task, in that the animal needs to maintain a constant internal representation of the start point on a given trial, but to reset this representation with each new trial. Surprisingly, the animals did not seem to be able to do this, raising questions about their ability to recall recent events (akin to episodic memory in humans) or their ability to learn variable goals. The experiments point to the critical importance of understanding what, for an animal, constitutes a goal and how much variable information it is able to maintain on-line as opposed to in a long-term store.

The final two papers in this special issue delve further into this issue of goal-directed, as opposed to home-directed, navigation. Goal-directed navigation is more complex than homing in that the agent needs a representation not only of its current location but also of the goal location, and some means of computing an efficient path between them (accounting, if necessary, for obstacles and short-cuts). Gorchetchnikov and Hasselmo simulate the problem of a rat trying to compute a path to one among several possible goals. Using a model that emulates properties of the rat hippocampus, together with important associated areas such as prefrontal and entorhinal cortices, they simulate navigation to the closest or the most salient of several goals, using a virtual environment of the kind that behavioural scientists frequently use in the laboratory and producing remarkably similar behaviour. Finally, Chavarriaga *et al.* model a situation that is currently generating considerable interest among navigational neurobiologists, which is the interaction between two mechanisms of navigational decision-making in rats: the so-called place response, in which animals select a trajectory by using the spatial layout of cues in the environment, or the cue response, in which animals in a well-learned situation act according to 'habit' (that is, they make a particular body turn at a familiar choice point, rather than referring to spatial cues in a map-like way). How does an animal choose between a place response and a cue response, and what happens if one previously successful strategy stops working? As before, it appears that animals have recourse to a variety of problem-solving methods in any given domain, and can switch between them. Understanding the rules by which such switches are made will be critical in both understanding animals and in designing artificial cognitive systems.

From the collection of papers in this issue, it seems that the interaction between researchers in artificial and natural domains continues to generate productive and interesting lines of enquiry. One issue, highlighted particularly by the biological papers in this collection, is the degree to which there may be a variety of ways to solve a particular problem, with the navigational system needing to decide which method to use. This was seen, for example, in the interaction between geometry versus other cues in guiding spatial orientation (Cheng), between visual and path integration cues in the selection of homing direction (Dudchenko and Bruce), in making choices among a number of possible goals (Gorchetchnikov and Hasselmo) and in the competition between responding according to habit (fast and efficient) versus responding according to spatial cues (slower but more flexible; Chavarriaga *et al.*). In each case, it seems that a decision needs to be made between competing domains about which will most effectively solve a given navigational problem. Sometimes, however, intelligent-looking solutions may break down in unusual situations: as, for example, when the remarkable homing capacities of rats are foiled by simply varying start location (Martin *et al.*). Such breakdowns in performance are often frustrating to biologists, yet yield valuable insights into the workings of the underlying mechanisms.

The other interesting question arising from this special issue, which was brought to the fore by several of the computational papers and also by Wallraff's discussion of pigeon homing, is the way in which sophisticated behaviours may arise from relatively simple algorithms, if these are constructed the right way. For example, it may not be necessary to decompose the elements of a visual scene into component landmarks or distances in order to home effectively (Vardy and Möller) or build a map (Ohnishi and Imiya), and it may not be necessary to encode metric relations to navigate accurately over long distances (Wallraff). Biologists may thus sometimes look for cognitive complexity where there need not be any, and it is useful to be reminded of this. It seems likely that living brains use a mixture of sophisticated but slow versus low-level but fast techniques, according to need: again raising the question of how the brain decides which process to recruit when. Clearly, the issue of switching between processing mechanisms is and will continue to be important in navigational research in both biological and artificial domains.

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References

K. Cheng, "A purely geometric module in the rat's spatial representation", *Cognition*, 23, pp. 149–178, 1986.
A.S. Etienne and K.J. Jeffery, "Path integration in mammals", *Hippocampus*, 14, pp. 180–192, 2004.
K.J. Jeffery, J.G. Donnett, N. Burgess and J.M. O'Keefe, "Directional control of hippocampal place fields", *Exp. Brain Res.*, 117, pp. 131–142, 1997.
B. Webb, "What does robotics offer animal behaviour?", *Anim. Behav.*, 60, pp. 545–558, 2000.