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Magnetic Sense

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The remarkable ability to navigate over long distances, associated with either migratory or homing behaviour is common to many animals. Examples are seen in a wide range of taxa including insects, birds, fish, crustacea and mammals. These innate behaviours make use of a range of sensory receptors (Box 1), allowing animals to respond to environmental stimuli and navigate across unfamiliar territories.

Migration is defined as the regular and intentional mass movement of animals from a breeding area to another area where they do not breed. Migratory movements are regulated by internal clocks in response to environmental cues. The Kūaka or Bar Tailed Godwit migrates 11,000 km annually from breeding grounds in the tundra of Alaska to the rich feeding grounds of the New Zealand tidal mud flats. As with many migratory journeys, adults leave the tundra in advance of the juveniles, providing clear evidence that this behaviour is innate and not learned.

Fig 1: Kūaka-Bar Tailed Godwit. Miranda, New Zealand
Image: J Bay

Homing is the ability of an animal to return to its nesting site after travelling beyond this site, usually to find food. While this is often across territories which are familiar, this is not always the case. The Toroa or Albatross exhibit homing behaviours, flying across vast areas of the southern oceans to feed, returning to their breeding grounds in New Zealand and the Sub-Antarctic Islands. Bees similarly can return from distances up to 10 kilometres from their hives.

Understanding the mechanisms by which animals **navigate** across unknown territories has been the focus of interest and challenge for scientists for many years. In both homing and migration the animal must navigate from starting points beyond the reach of sensory information relating to their goal location. This means that the animals must be able to sense **location**, to determine their starting point, and **direction**, to determine the path they will take in order to reach their goal location. This ability is clearly demonstrated in the domesticated Homing Pigeon, *Columba livia.* In addition to being able to return to their nest site after feeding, homing pigeons are also able to return to their nest from distant and unfamiliar sites. Homing pigeons transported to unfamiliar starting sites, (meaning they have not navigated the outward journey), when released still find their way back to their nest site, even if transported to the release site under general anaesthesia. This means that as well as having some form of compass to determine direction, the homing pigeon must also be able to determine where it is starting from, demonstrating that the homing pigeon has a sense of location.

Box 1 Sensory receptors used in navigation behaviours

- Audioreceptors - sound
- Chemoreceptors - chemicals
- Electroreceptors - electrical fields
- Magnetorecptors - magnetic fields
- Mechanoreceptors - touch, pressure, gravity, stretch, movement
- Photoreceptors- light / vision
- Propioreceptors - muscle tension
- Thermoreceptors - temperature

Environmental Stimulus
↓
Sensory Receptor
↓
Response

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NGĀ PAE O TE MĀRAMATANGA

Research Team

Professor Michael Walker, a scientist from the University of Auckland's School of Biological Sciences and co-director of Ngā Pae o te Māramatanga, New Zealand's Māori Centre of Research Excellence, is an expert in the field of animal navigation. Michael leads a scientific research team at the University of Auckland who in collaboration with scientists from California Institute of Technology and the University of Hawai'i, have made a number of significant discoveries relating to the use of magnetic sense in animal navigation. As well as answering key questions relating to the mysteries of migration and homing, this work has potential application in understanding the environment, the fishing industry and understanding of navigational mechanisms.

Fig 2: Professor Michael Walker © New Zealand Herald

Fig 3: Kūaka - Bar Tailed Godwit. Alaska
Image: Tim Bowman US Fish and Wildlife

Research Question

The incredible journeys made by species such as Kūaka (Bar-Tailed Godwit), Trout and Tuna are all thought to make use of the magnetic sense as the primary navigational compass. Scientists want to work out how species such as the Godwit and Muttonbird determine their path and overcome obstacles on the journey. How do they detect, process and apply information to determine their pathways?

Key research questions that that Professor Walker's group have been addressing are:

- **How do animals use the Earth's magnetic field to determine position?**
- **Do domesticated homing pigeons use information about the Earth's magnetic topography to orient themselves when determining position?**

Choice of Research Species

Although interested in understanding the mechanisms of navigation used in long distance migration in wild animals and insects, the research group used domesticated homing pigeons in their investigations. Homing pigeons are used as a model animal in the same way as the laboratory rat or mouse is used in medical research. Being domesticated, the pigeons occupy a loft which they use for eating, drinking and breeding. This means that they have one defined place that they will always return to, unlike wild pigeons which utilise a larger home range. The domesticated pigeons are easy to care for, inexpensive, abundant, and produce navigational behaviour on demand, making them an ideal species to use in this research. The information that is found about the behaviour of the homing pigeons can be applied to understanding the behaviour of species such as the Godwit, Muttonbird (Sooty Shearwater), Tuna and Trout, all thought to use magnetic sense. Following either birds or fish in the wild is extremely problematic. The use of modelling in a highly accessible animal such as the Homing Pigeon allows scientists to determine information that would be impossible in other species that travel much larger distances.

Literature Review

A scientific team does not work in isolation. One of the most important components of science is the communication of findings. This allows scientists to engage in debate and build on the findings of others within the scientific community. Before we look at how the research team answered these questions, we will take you through the information that they or others did know that was useful in determining how they would go about investigating their questions.

The Earth's Magnetic Field

The Earth is composed of four layers (Fig 4). The solid inner core is surrounded by a molten outer core of iron. This in turn is surrounded by a semi-liquid mantle on which the solid crust floats. Convection currents within the molten core create a strong magnetic field which can be represented as a bar magnet (Fig 5), but tilted 11 degrees from the spin axis of the Earth. This tilt creates the difference between geographic north and magnetic north. Notice that in Fig 5 the south pole of the magnet representing the Earth's magnetic field lines up with the Earth's magnetic north pole. This is because unlike magnetic poles attract. The field lines in figure 5 represent the intensity and inclination of the magnetic field which increase systematically between the magnetic equator and the magnetic poles. If you compare these to the pattern created by the iron filings around the bar magnet (Fig 6), you will notice the similarity. The arrows indicate the direction of the magnetic force while the distance between the lines represents the strength of the field. The closer the lines are together, the stronger the magnetic field so that the Earth's magnetic field is strongest at the poles. When you use a compass to determine your direction, the compass needle is actually a magnet which will line up with magnetic north and determine where you are facing in comparison to magnetic north. In the same way, if an animal has a magnetic receptor, it will be able to determine direction.

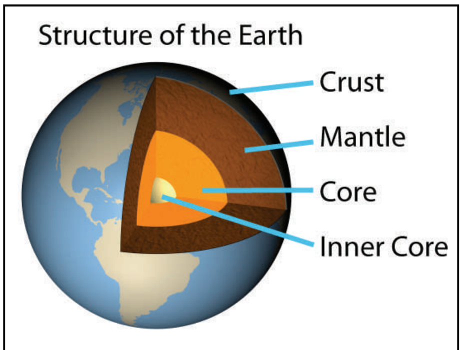


Fig 4: Structure of the Earth

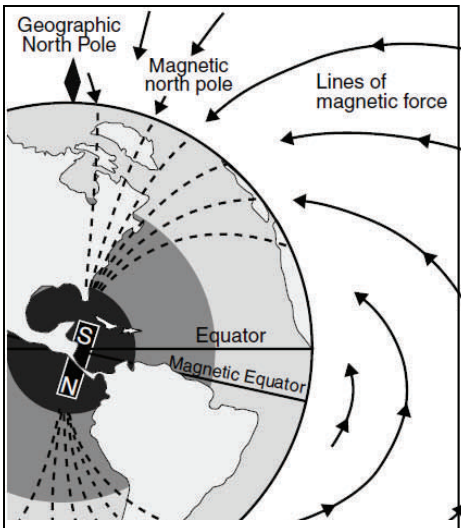


Fig 5: The main magnetic field of the Earth
From Walker et al 2002 Current Opinion in Neurobiology 12:735-744 (Used With Permission)

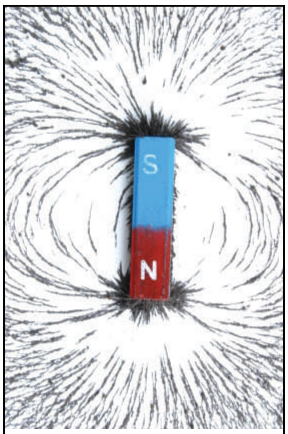


Fig 6: Magnetic Field of a simple bar magnet

In addition to the strong magnetic field created by the Earth's core, localised magnetic fields are created from magnetised rocks in the crust. These localised fields are known as ***anomalies*** and although much weaker than the main magnetic field of the Earth, create observable variations (Walker et al 2002). Fig 7 shows the effect of these localised fields in the Auckland area. The red diagonal lines represent contours of equal intensity of the magnetic field produced in the Earth's core. The black contour lines show the variations in the magnetic field caused by magnetic anomalies. This map shows you the **magnetic topography** of the area that is added to the systematic variation in magnetic intensity that is produced in the Earth's core. The closer the lines are together, the steeper the gradient in the magnetic topography. Notice the effect of the volcanic island of Rangitoto on these contours. The high iron content in this volcanic rock is influencing the magnetic field, creating a local anomaly.

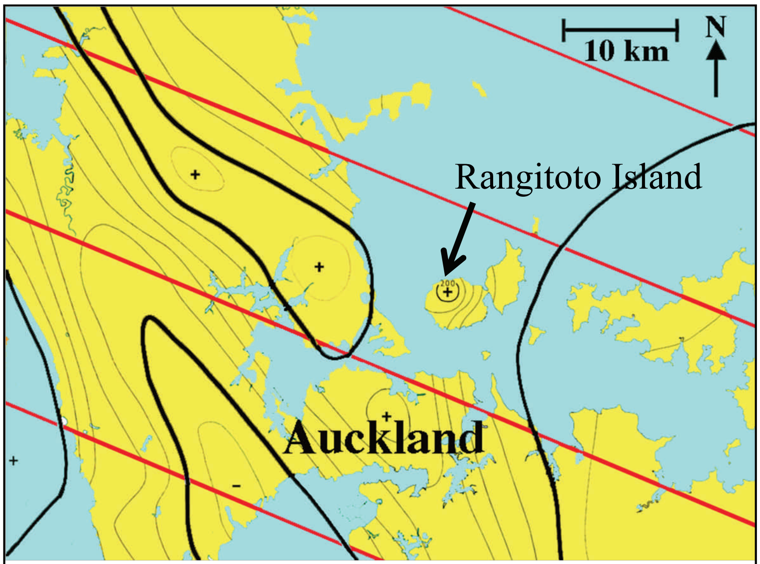
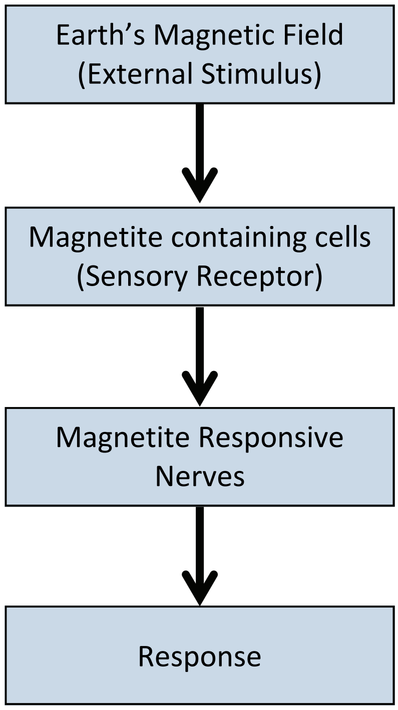


Fig 7: Non-systematic components in the Earth's magnetic field

What makes an effective environmental cue for navigation?

Animals have been shown to use a variety of environmental cues in navigation. These range from visual stimuli (such as the relative position of sun, stars, moon and location of landmarks) to detection of low frequency sounds (such as those created by waves breaking) and detection of magnetic fields. For an environmental cue to be of use to an animal in navigation, the cue must be consistent, vary systematically in space to provide information about specific points on the Earth's surface, be stable over time and provide enough accuracy to allow the animal to reach its specific goal destination. Although there is some variation in the Earth's magnetic field, there is adequate consistency to make this a viable environmental cue for navigation. Importantly, unlike other environmental cues such as the position of sun and stars which are inaccessible when there is cloud cover, the Earth's magnetic field will give consistent information that can be used to determine position and direction at all times and in all environments.

How can animals detect magnetic fields?



Organisms from bacteria through to higher vertebrates demonstrate an ability to sense the Earth's magnetic field. The fact that such a wide range of organisms are magneto-receptive suggests that the ability to sense the Earth's magnetic field evolved prior to the radiation of the animal phyla and shares a common origin in early prokaryotic organisms. Whether enabling taxic orientation responses in bacteria or navigation in higher vertebrates, the ability to sense the Earth's magnetic field, as with other sensory abilities, will have provided a selective advantage for these organisms. Over the course of time, magneto-reception in animals will have evolved to become more sensitive, eventually specialising to monitor both the direction of the magnetic field and variations in the intensity of the magnetic field (Kirschvink et al 2001).

Experimental evidence has shown that the receptor that allows bacteria and animals to sense the Earth's magnetic field uses **ferromagnetic** materials such as magnetite (Fe_3O_4). In bacteria and eukaryotic algae that are magneto-taxic, chains of magnetite or greigite (Fe_3S_4) produce a magnetic moment (a moment is a measure of the strength and direction of magnetism produced by a system) large enough to rotate the cells so that they line up with the Earth's magnetic field (Schuler et al 1999). If the bacteria or algae naturally seek the north pole of the magnetic field, this can be reversed by exposing them to pulse-remagnetization experiments (Kalmijn 1978), in the same way that you can reverse the poles on a magnet This ability to reverse magnetic direction is only found in ferromagnetic materials. Similar experiments on bees and birds have demonstrated the same pole reversal effect, suggesting that they too contain some kind of ferromagnetic sensory receptor (Kirschvink et al 2001).

What is known about the behaviour of Homing Pigeons?


Fig 8: Homing Pigeon, *Columba livia.*

Homing Pigeons display consistent homing behaviours, are easily accessible, and have been studied extensively, making them ideal study animals. Homing pigeons taken from their nest sites (or lofts) to new locations where they are released, consistently return to their lofts. In order to do this, they must be able to determine their position at the release site in relation to the position of their loft, and therefore calculate the direction in which they need to fly. Two well-known experiments demonstrate this ability. In the first experiment pigeons wearing frosted contact lenses, which prevent form vision, were taken to a previously unknown location and released. They returned to within 0.5 - 2 km of their loft but did not enter the loft, presumably because they cannot see it (Schmidt-Koenig & Walcott 1978). In the second experiment one group of pigeons were anaesthetised and transported to the release site, while a second group were transported without anaesthesia. There was no difference between the initial orientation that the pigeons from the two groups flew in, or their ability to return to their lofts (Walcott and Schmidt-Koenig 1973). A third experiment (Walcott 1978) showed that when homing pigeons are released from positions which show magnetic field anomalies (Fig 7), they are consistently disoriented. The degree of disorientation was proportional to size of the local disturbance in the magnetic field.

Research Method

To find out whether pigeons use information about the Earth's magnetic field to orient themselves when determining position, the scientific team studied the initial behaviour of pigeons when they were released from sites around an magnetic anomaly that caused changes in intensity of the Earth's magnetic field. The scientists hypothesised that if the birds were reliant on information about systematic variation in the magnetic field to determine their location, the anomaly (which caused a disruption in the Earth's magnetic field) would confuse the birds and potentially confuse their initial flight behaviour.

The release site:

The birds were released at sites in and around the **Auckland Junction Magnetic Anomaly** (JMA). This is a specific location where a cluster of massive rock slabs approximately 1.6 km below the Earth's surface causes a detectable distortion in the Earth's magnetic field. A magnetic map was produced by flying in a small plane backwards and forwards across this area at an average altitude of 300m. A tool called a magnetometer was used to take 5671 measurements of the magnetic intensity of the study area, allowing the magnetic topography map to be created.

Global positioning devices:

The research team built miniature global positioning devices (like a GPS) to record the flight trajectories of the pigeons as they homed from release sites. These devices were attached to the backs of the pigeons with a harness and were configured to operate continuously, recording one position fix per second.

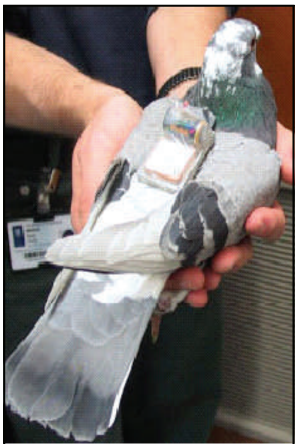


Fig 9: Pigeon with GPD

Experimental animals and releases:

The test birds belonged to a local pigeon racer. The birds all had training and racing experience from locations south of the loft, over distances of up to several hundred kilometres. The test birds were all adults. Most were between 2-3 years of age; a few individuals ranged up to 8 years in age. Equal proportions of males and females were used. Prior to the release, the birds were trained for several weeks to carry the harness and weight of the tracking devices.

To determine whether the flight behaviour of the birds varied in relation to geomagnetic intensity, the research team released pigeons at 15 sites in and around the magnetic anomaly. At each site one bird was released per day and each bird was released only once at each site (so that the release sites were always new to the birds). To control for the potential effect of local weather, all flights occurred on days when the orb of the Sun (full spherical shape) was visible and when wind speeds were less than 15 kmh^{-1}.

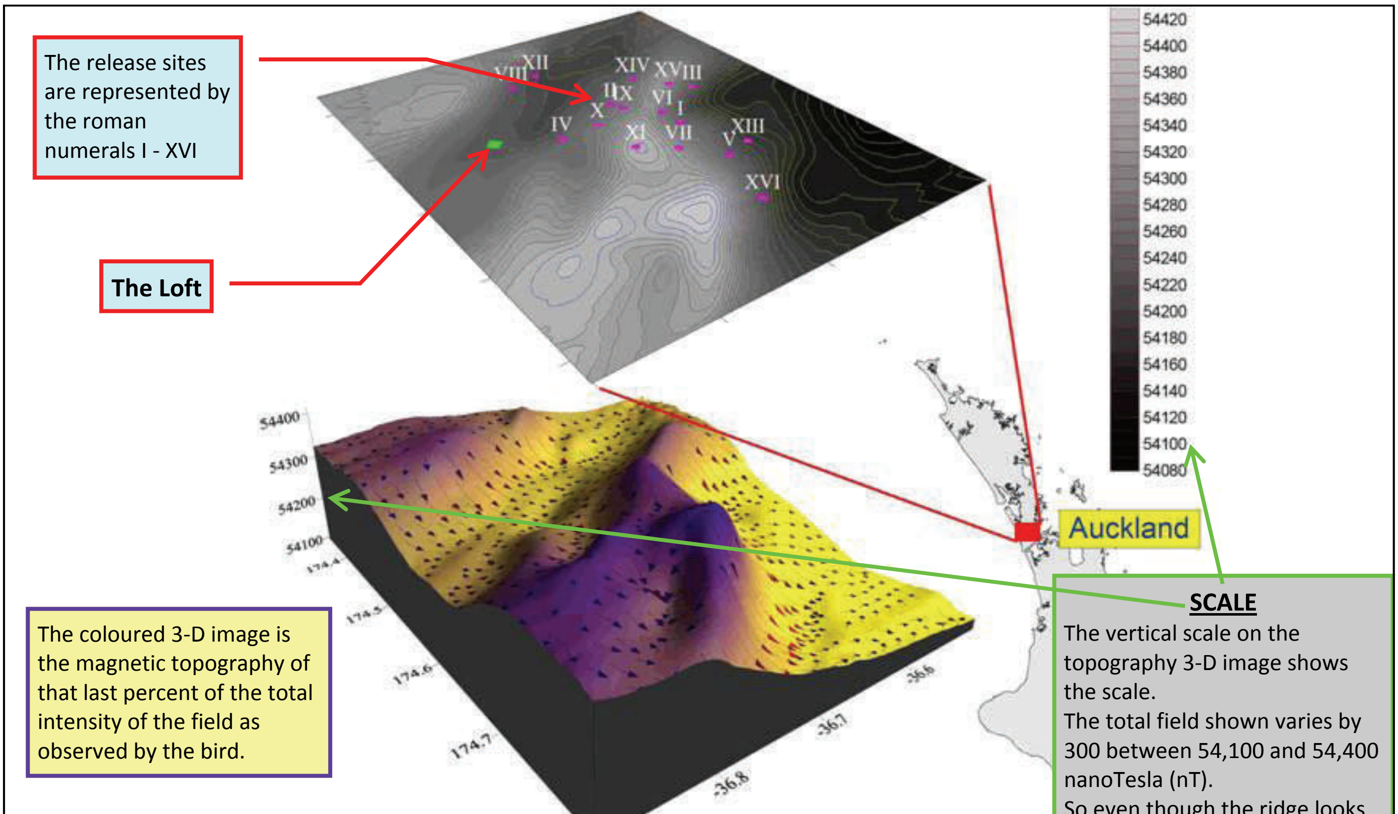


Fig 10: Auckland Junction Magnetic Anomaly
Courtesy Todd Dennis, University of Auckland

Results

The research team recovered 92 complete flight trajectories of pigeons from the point of release to the location of the loft. They found that the 92 pigeons frequently showed segments of flight aligned to the contours or slope in magnetic intensity within the first 4 km of flight from the release site. This was a completely new finding. The alignments of flight to magnetic topography were shown to be non-random for 59 of the 92 birds and could be grouped into three categories:

(a) those that flew parallel to the anomaly's magnetic field (29 flight trajectories)

(b) those that flew perpendicular to the anomaly's magnetic field (33 flight trajectories)

(c) those that flew a box-like pattern, changing from parallel to perpendicular and back to parallel to the anomaly's magnetic field (42 flight trajectories).

Some individual birds showed more than one type of response. In all cases, as soon as the birds were beyond the anomaly's magnetic field, they corrected their flight path and flew in direction of their loft. The probability of observing these numbers of significantly aligned trajectories by chance was calculated to be 5.22×10^{-16}, 5.83×10^{-20}, and 5.09×10^{-30}, respectively.

Figure 11 shows the results from different release sites (the bold yellow dots). In map (a) in each case the birds have flown in a direction parallel to the magnetic field created by the anomaly rather than flying in the direction of home. Follow the call-outs on the diagram to work through what each part tells you about the flight of the birds.

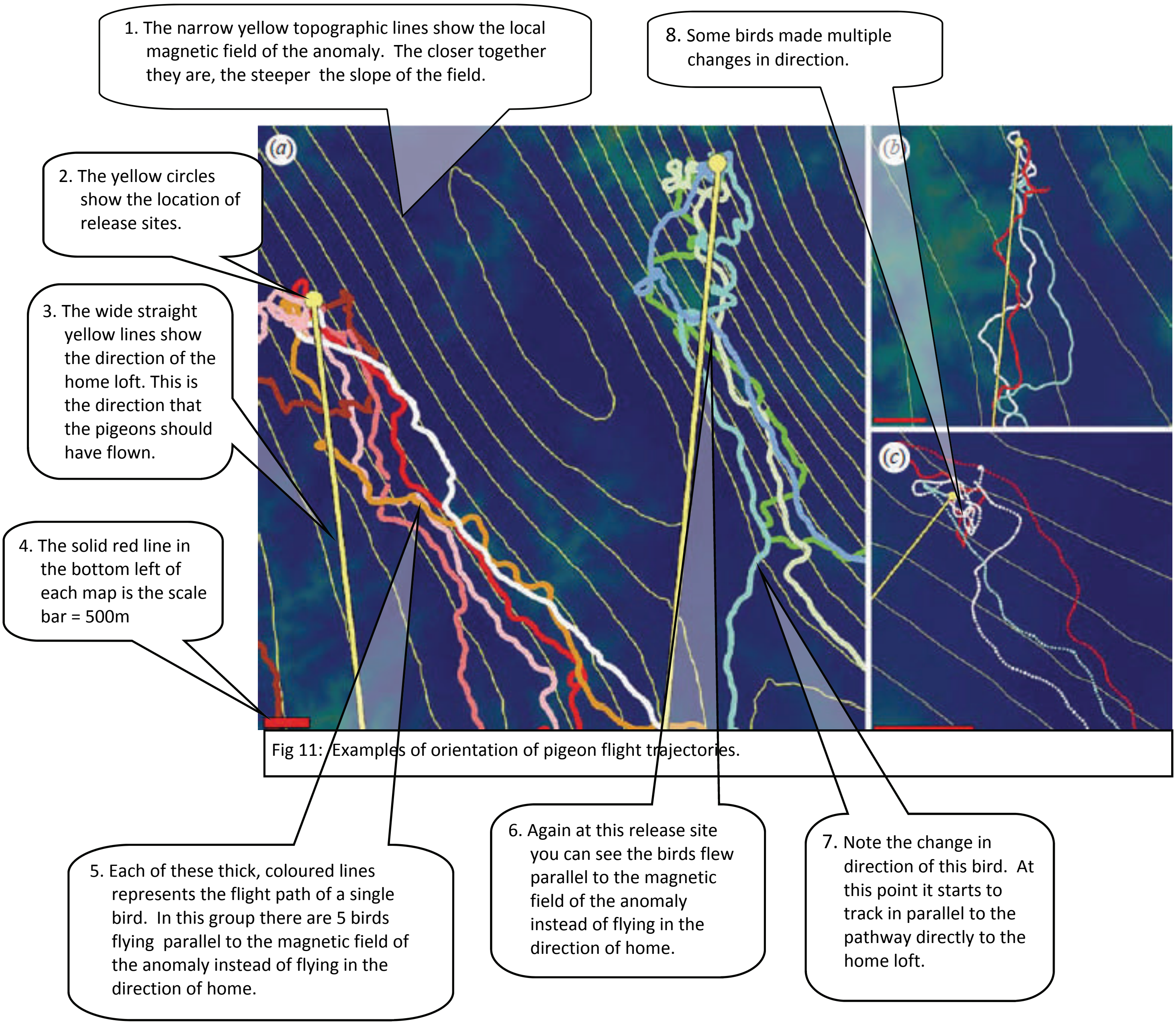


Fig 11: Examples of orientation of pigeon flight trajectories.

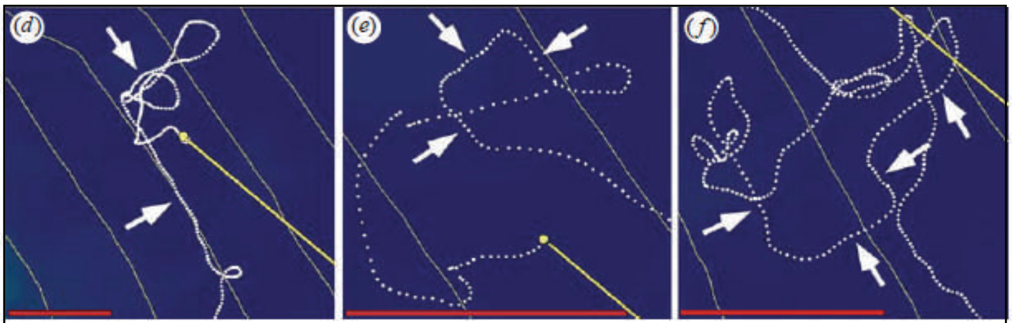


Fig 12: Detail of L-shaped and box alignments in the trajectories of single birds. Arrows indicate the alignment of individual birds

Figure 12 gives the detail of the trajectories of three different birds, showing the L-shaped pathway (d) taken before aligning to the magnetic field, and box-shaped pattern (e and f) where the sides of the "boxes" oriented parallel and perpendicular to the magnetic field of the anomaly. The box-shaped trajectories may indicate that the birds were sampling the geomagnetic field to gain information about latitude and longitude.

Other potential navigational cues which may influence homing behaviour such as gravity, surface topography (elevation and slope of the land) and landscape features were assessed. The results showed that geomagnetic intensity at the study site was not strongly associated with other navigational cues **so it would seem that the magnetic field was the only information used by the birds during the homing flights.**

Discussion

There is significant evidence that birds and other animals are sensitive to magnetic fields and have an internal compass used to determine position. However it is also known that position alone will not allow animals to build the navigational maps that are needed to accomplish journeys required for successful homing and migration. To do this the animals must be able to determine both **location** (position relative to their destination) and the **direction** in which they should move to reach their destination. The results of this investigation indicate that the pigeons are using the information provided by the magnetic topography (difference between magnetic intensity at different points), to determine their position. The magnetic anomaly appeared to confuse the birds and disrupt their ability to determine their position. As soon as they were out of the magnetic anomaly, the birds corrected their alignment and flew in the direction of their loft. This indicates that the confusion as to their position was being caused by the unexpected magnetic field experienced as a result of the anomaly.

A wide range of organisms are known to have the ability to sense the Earth's magnetic field. Very small crystals of magnetite have been found in the beaks of pigeons and in the nose of trout which are thought to detect magnetic fields. In order to use the information from the magnetic field to create a navigational map, animals would need to be able to determine both the direction and intensity of the magnetic field. The research team have suggested a hypothetical model which may enable this to occur (Fig 13). In this model, the chain of magnetite crystals in a cell would be attached to a pivot point in the cell membrane and be connected by filaments to ion channels in the cell membrane. As the chain moves in response to the magnetic field, it would pull on the filaments and open the ion channels. This would create neural activity and enable a detectable response.

Fig 13 as constructed shows variants of the same idea with Fig 13b the more advanced/complex. To generate a signal from the magnetite, it must be connected to the cell membrane somehow. That means it is not free to rotate like a compass needle. By having many cells with orientations distributed over a sphere, both the direction and the intensity of the field can be determined. Extra links to ion channels will increase resolution at the single cell level.

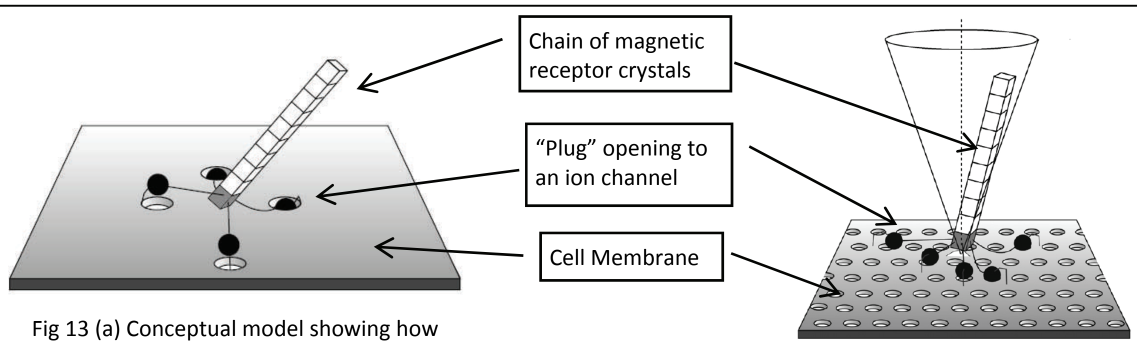


Fig 13 (a) Conceptual model showing how magnetic field direction may be detected. (Walker et al 2002)

Fig 13 (b) Conceptual model showing how magnetic field intensity may be detected. (Walker 2008)

Future Research:

The research team are working to test the hypothetical model that they have proposed (Fig 13) to explain how at a cellular level the pigeons are detecting and processing this information. They are also studying other species of interest such as sharks and bats, looking for similar patterns of behaviour to those seen in the pigeons. Evidence that other species are displaying similar behaviour would suggest common mechanisms at a cellular level, and indicate that what has been learnt about the behaviour in the pigeons can be applied to these species.

Potential application of knowledge:

How could this knowledge, and eventually full understanding of how animals use magnetic sense, be applied? **Fisheries Science** is one such area. Species such as tuna, turtles, sharks and trout all make significant journeys. Understanding these journeys and the location of the animals is useful in managing both conservation and fishing within the marine environment, however it is very difficult to track and follow marine species as traditional radio and GPS tracking devices do not work in the marine environment. What is required is a system that replaces the GPS under the sea. Reverse engineering the system that pigeons use for determining position will permit development of devices that operate as geomagnetic positioning systems. It would then be possible to attach such devices to animals, track journeys and record information environmental along the animal's track. Currently detection systems are designed to detach from the animals after a period of time and float to the surface where the information can be retrieved via radio signal to satellite. Much more can be learned and developed in this area.

Possum control is another place where application of knowledge could be used to improve management of the species. Possums pose huge problems for New Zealand, damaging our forest environments and endangering many native species - both plant and animal. The technologies that were developed to study the pigeon journeys can be applied to understand the journeys of possum and used to track where these animals are living (and therefore causing harm to the environment). Currently management of possums in New Zealand uses 1080 poison, which while very effective at killing possums, also kills other species, including endangered species in forest environments and farm animals. The research team are exploring how more effective environmental management may be achieved using knowledge derived from greatly improved tracking of this species in the wild.

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