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SINAL MAGNETITE AND DIRECTION FINDING

R Robin Baker

Direction finding by animals, including man, may use magnetic particles in the sinus region. Manipulation of these particles could improve, as well as destroy, the sense of direction

A little over a century ago, in 1855, a German scientist, Dr von Middendorf, suggested that the ability of animals to home was based in some way on a sense of the earth's magnetic field. The idea was generally ridiculed. For example, when accused of believing in a magnetic sense, Alfred Newton, the first professor of zoology at Cambridge, replied 'I had no need to declare my disbelief in Dr von Middendorf's magnetic hypothesis, for I never met with any man that held it'.

Now, after a century of often bitter controversy, good experimental evidence from the past fifteen years has led to general acceptance that animals do indeed possess a sense of direction based on detection of the earth's magnetic field. Biologists still await, however, the first positive identification of a magnetoreceptor, a sense organ on which this magnetic sense is based. Some of the research into the site and nature of magnetoreception involves organisms such as bacteria, moths and bees. Most, however, is concerned with vertebrates (animals with backbones, such as fish, amphibians, reptiles, birds and mammals, including man) and, for these animals, attention is turning more and more to magnetic deposits being discovered in the sinus region. It is the possible involvement of these sinal deposits in direction finding that is the subject of this article.

Animals have two major uses for directional information. The simpler use is to distinguish between and identify the global directions that we

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label north, south, east and west, etc. The more complex use is to locate the direction of 'home' whenever the animal finds itself in unfamiliar terrain. Both of these uses have been the subject of extensive tests.

Evidence for magnetoreception

Experiments on the detection of compass direction through sensitivity to the earth's magnetic field have usually involved either migrant birds confined in cages or blindfolded humans seated on rotating wooden chairs. Many well known species of birds (e.g. swallows, warblers) migrate towards, and often across, the equator in autumn and back to their breeding grounds in spring. When such a bird is confined in a cage during the migration season, it shows behaviour that is very convenient to the experimental biologist. Not only does it become very restless at the same time of day or night that its free-living relatives are migrating but it also shows a preference to hop and flutter in the same compass direction as them. Thus, a bird from the northern hemisphere prefers to hop in its cage toward the south in autumn and north in spring. Moreover, this preference continues to be shown even if the bird is caged in a darkened room with no view of the sky.

The first evidence that these caged birds are detecting the appropriate compass direction by sensing the earth's magnetic field was provided by work begun in the mid-1960s at Frankfurt University. The cages in which the birds were held had a number of perches arranged radially and pointing in different compass directions. Each perch was fitted with an automatic monitoring device that recorded every time the bird landed. In addition, the cages were surrounded by electromagnetic coils which permitted the magnetic field through the cage to be changed. Care was taken to produce artificial fields similar in intensity to the earth's (46000 nT at Frankfurt). Results showed that the birds oriented with respect to the direction of the lines of force through their cage, no matter whether the field was real or artificial, showing a preference in autumn for magnetic south and in spring for magnetic north.

The first bird to be studied in this way was the European robin which, on mainland Europe, unlike in Britain, does migrate south in autumn. Now, the number of species of birds known, through this type of experiment, to have a magnetic compass sense has just about reached double figures. Most work continues to be done at Frankfurt but some has also been carried out in the USA.

As far as the magnetic compass sense of humans is concerned, over a thousand subjects have now taken part in rotating chair experiments carried out by my colleagues and I at Manchester. The subject sits on a rotatable wooden chair and dons blindfolds and earmuffs (figure 1). Most experiments have been carried out in a wooden hut on the edge of woodland in rural Gloucestershire, 100 m from the only buildings for a 1 km radius. After a few turns, first one way then the other, the chair is stopped and the subject tries to estimate the compass direction in which he or she is facing. A single test run on a subject involves nine such stops. Each estimate gives an angular error (e.g. when facing N, an estimate of N gives an error of 0°, an estimate of S gives an error of 180°, of W an error of −90°, of E +90°, and so on). At the end of the test the mean angular error ($\bar{e}$) for the nine estimates is calculated using circular statistics.

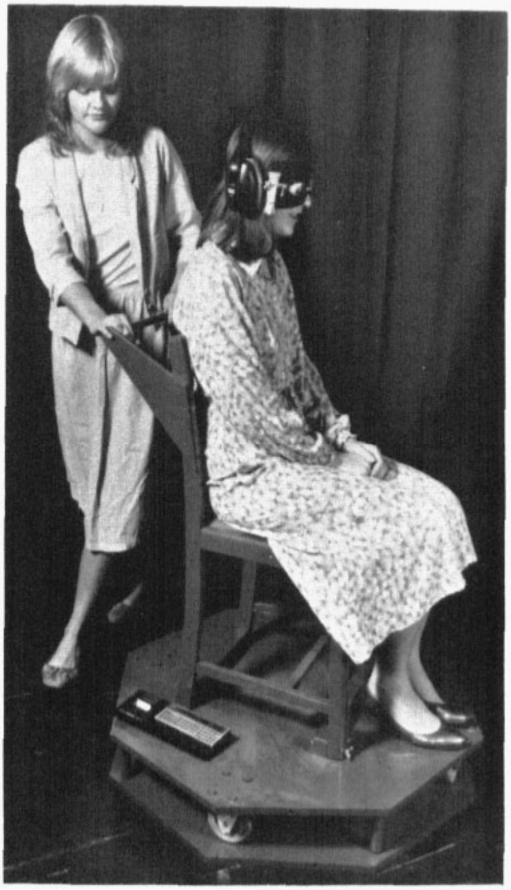


Figure 1 The rotating chair used in the Manchester 'chair' experiments. The pocket computer shown on the base of the chair is normally carried by the experimenter throughout the experiment. This selects and prints out a sequence of random directions, prints out the subject's estimates, and analyses the results (*photo by Les Lockey*)

In some tests the magnetic field through the head is altered by means of bar magnets. In others it is

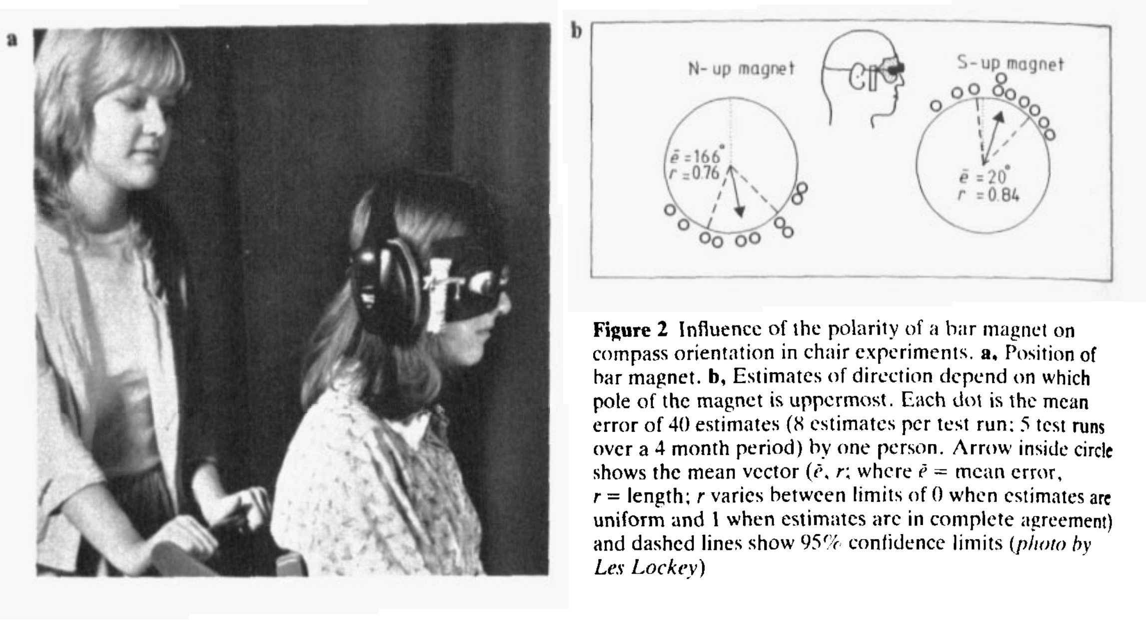


Figure 2 Influence of the polarity of a bar magnet on compass orientation in chair experiments. **a**, Position of bar magnet. **b**, Estimates of direction depend on which pole of the magnet is uppermost. Each dot is the mean error of 40 estimates (8 estimates per test run; 5 test runs over a 4 month period) by one person. Arrow inside circle shows the mean vector ($\bar{e}$, r; where $\bar{e}$ = mean error, r = length; r varies between limits of 0 when estimates are uniform and 1 when estimates are in complete agreement) and dashed lines show 95% confidence limits (*photo by Les Lockey*)

unaltered, subjects wearing brass bars. Elaborate precautions are taken to ensure that neither the subject nor the experimenter knows whether, in a particular test run, the subject is expected to judge direction accurately, to produce random results, or to produce a mean error of 180°.

It might be expected that on a rotating chair, people might try to judge direction by noting their starting position before being blindfolded and then counting turns using some form of inertial sense. In fact, people are very poor at judging turns under such conditions and data show that our chair experiments are not primarily testing an inertial sense. For example, subjects who are 90° or more in error on their first estimate in a test run are just as likely (in fact slightly more likely) to be accurate with their next estimate than subjects who are 0° in error on their first estimate. This could not happen if the sense being tested were inertial and we can safely conclude that our rotating chair is testing primarily a sense of direction. That this sense is based on magnetism has been shown by a variety of tests. To choose just one example (figure 2), if a bar magnet (pole strength approximately 20 mT) is placed vertically on the right temple, the mean error is nearly 0° if the S pole of the magnet is uppermost but nearly 180° if the N pole is uppermost.

The fact that estimates of compass direction by birds and humans can be manipulated experimentally in a more or less predictable way suggests that the use of the earth's magnetic field to judge compass direction may be fairly straightforward. The situation is less clear cut, however, for both humans and birds, when we consider the use of the earth's magnetic field to judge the direction of home after experimental displacement.

Homing experiments

Displacement or 'homing' experiments on birds involve collecting the birds from their 'home' (invariably homing pigeons from their loft) and taking them on a journey to a release site tens, or sometimes hundreds, of kilometres away. The birds are released singly and the compass bearing at which each vanishes from site is recorded. The mean vanishing bearing for the group is then calculated by circular statistics and compared with the direction of home.

The fact that homing pigeons use the earth's magnetic field to follow their outward journey was discovered by accident. Wolfgang and Roswitha Wiltschko from Frankfurt noticed that when they transported pigeons to the release site in the back of their VW squareback, the birds were disoriented upon release. When displaced in other vehicles, however, their mean vanishing bearings were oriented toward home. This 'VW effect' has since been confirmed in the USA. The Wiltschkos eventually traced the cause to the anomalous magnetic fields in the back of their VW, the pigeon cages being sited just above the generator. Experiments (using non-VWs) in which the magnetic field through the pigeons' cages was changed artificially during the journey confirmed that without a normal magnetic field during displacement, pigeons were disoriented upon release.

One problem with this research is that it has not yet been possible to change in a predictable way the direction in which the pigeons disappear. For example, Jacob Kiepenheuer tested the effect of reversing the magnetic field experienced by his pigeons during displacement. Other pigeons, the controls, were transported in an unaltered magnetic field. However, instead of setting off in a direction opposite from the controls, his experimental birds were only 31° off course when released.

At Manchester we have been carrying out similar experiments on humans by means of our so called 'bus' experiments. Bus-loads of blindfolded subjects are transported along winding routes out of Manchester and then asked, while still blindfolded, to estimate the compass direction of 'home' (Manchester University in most of our tests). With an unaltered magnetic field through the head, a relatively weak but nevertheless statistically highly significant ability to judge home direction under such conditions emerges. For example, if, for each journey, the mean error of all estimates is calculated, we find that for our 31 journeys to date, the mean error (where home direction = 0°) has been less than 90° on 25 occasions. Were the estimates random, of course, a mean error less than 90° would occur on only half the journeys. There was some initial controversy over the Manchester results when James Gould carried out four journeys at Princeton. The results were unimpressive even though three of the four mean errors were less than 90°. Since then, however, 15 further journeys accumulated through research at Princeton, Cornell, Albany, Swarthmore and Short Hills in the USA and Durham and Keele in Britain have *all* produced mean errors less than 90°.

In one of our series of bus experiments at Manchester, subjects wore electromagnetic helmets made of PVC and supporting lateral copper coils (figure 3a) powered by a 9 V battery. A false connection at the back of half of the helmets produced control subjects with an unaltered magnetic field through their head. The estimates of the compass direction of home made by controls and experimentals differed significantly (figure 3b), those by experimentals being anticlockwise of controls on the same journey on 12 out of 14 occasions. The mean angular difference between controls and experimentals was 43°. However, as for Kiepenheuer's pigeons, this difference does not correlate in any obvious way with differences in the direction of the lines of force experienced during the journey.

Figure 3 Influence of electromagnetic helmets on judgment of compass direction of home in 'bus' experiments. **a,** Subjects wearing battery-powered helmets. **b,** Each dot is the mean error of all estimates in home direction during a journey by subjects wearing activated helmets relative to the mean error for controls wearing deactivated helmets during the same journey (*photo by Les Lockey*)

The nearest result to a predictable rotation of orientation that has been achieved by manipulating the magnetic field during displacement was obtained for woodmice by Janice Mather and myself, working near Stroud in Gloucestershire. If woodmice are caught, displaced 40 m or so, then tested in a special orientation cage, they orient toward the place where they were caught. They can do this even if they are prevented from seeing their surroundings throughout the entire experiment. However, if the magnetic field they experience during displacement is reversed, the direction in which they orient also changes. The change observed is still not the predicted 180°, but is nevertheless a respectable 131°.

Although in recent years most attention has been given to experiments involving manipulation of the magnetic field during displacement, the most predictable result in homing experiments to date was achieved by Charles Walcott and his colleagues at Stonybrook when they changed the magnetic field through the head of homing pigeons upon

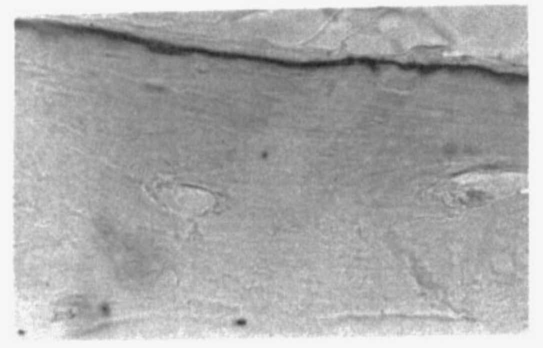


Figure 4 Section through bone from the wall of the sphenoid sinus of a 57-year-old woman. Bones that form the walls of the sphenoid and ethmoid sinuses in humans are magnetic and contain iron deposits that, after staining, show as a dark line 5 µm or so beneath the bone surface (*photo by Les Lockey*)

release. Special battery-powered 'cap-and-collar' coils were used. In some, termed S-up coils, the direction of the current was such that, when placed where the pigeon's head would be, the north-seeking pole of a dip needle pointed downwards, as in the earth's normal field. In others (N-up), the north-seeking pole pointed upwards. Under sunny skies both groups of birds set off towards home. Under overcast skies, however, only the S-up birds produced a mean vanishing bearing towards home. N-up birds set off in the opposite direction.

With evidence now beginning to emerge that fish, such as salmon and tuna, and amphibians, such as salamanders, can also find direction from the earth's magnetic field, many people are now beginning to think that such an ability will eventually be found in all vertebrates. Attention now turns to the search for the sense organ on which this ability is based.

The search for the vertebrate magnetoreceptor

As those of us involved in the search for magnetoreceptors pore over our various bits of animal tissue, we have to keep reminding ourselves that the discrete structure for which we are looking may not even exist. Many mechanisms of magnetoreception have been suggested, particularly with regard to birds, none of which would require such a structure. One proposal, for example, is that a flying bird might act as a linear conductor which, as it moves through the lines of force, would set up a small potential difference between its two ends. Alternatively, air friction on a bird's feathers could set up electrostatic forces which might react to the earth's magnetic field. Lymph tubes could act as conductors in which an electromotive force is generated or perhaps a conducting loop (such as a semicircular canal in the ear), when it oscillates in the earth's magnetic field, could generate an alternating current by the dynamo principle. All of these suggestions have inherent difficulties, not least of which is that they all require detection of tiny effects against considerable background noise.

The latest suggestion not to involve a special and discrete magnetic sense organ is that detection of the magnetic field might take place in the eye, in the molecules of the retina, as a byproduct of the normal visual process. Specifically, the suggestion is for an optical or radio frequency double-resonance process involving the lowest excited triplet state of a particular molecule (rhodopsin being the favoured candidate). These triplet states have a magnetic moment and their energy variations with the magnetic field are anisotropic, depending on field magnitude as well as on field direction.

If any of these suggestions is correct, we are wasting our time looking for a specialised magnetoreceptor. However, none can lay claim to any positive experimental support and currently by far the most favoured hypothesis is that magnetoreception depends in some way on deposits of magnetic particles in specialised tissue. Moreover, most people favour the idea that these particles will be of the magnetic material often known as lodestone, the ferric–ferrous oxide, magnetite ($FeO.Fe_2O_3$).

When Heinz Lowenstam first described the presence of magnetite in the teeth of chitons, unexciting cold-blooded molluscs that live on rocky seashores, he met considerable resistance, verging on ridicule, from the establishment of physicists and chemists. This was because it was widely known that, industrially, magnetite could only be manufactured at very high temperatures and pressures. Nevertheless, magnetite was present in these animals and, before long, Lowenstam and his colleagues had identified much of the biochemical pathway by which the magnetite was produced. Since then, magnetite has been confirmed in a wide range of organisms, from bacteria and bees to fish, birds and mice. Many biologists now see in the unique magnetic and conductive properties of magnetite, the ideal substance to form the basis of a specialised magnetoreceptor.

Just how the magnetite might convey directional information is a matter for less agreement. A number of suggestions have been made of which two examples follow, but these are very much at the level of working hypotheses. Perhaps, as the body of the animal moves within the magnetic field, the magnetite particles rotate, or try to rotate, to realign with the earth's field. As they do so, they could trigger sensitive cells which would relay information to the brain by nerves. Alternatively, it may be important for the magnetite deposits to exist in the form of a large and ordered array, particles with a particular size and spacing exerting a magnetic influence on each other. As the array turns within the earth's magnetic field, electrical, magnetic or even pressure changes could occur and trigger nerves ramifying through the tissue that holds the array.

The magnetite hypothesis has sent biologists scurrying on a search through the animal kingdom looking for deposits of magnetite, or other magnetic material, in a form discrete enough to be the basis for a magnetic sense organ. The initial stage of this search is to place selected pieces of tissue in a sensitive magnetometer. Once tissue has been found that consistently shows above-background levels of magnetic remanence, the next, and much more difficult phase, begins. This is to use histology, electron microscopy, electron diffraction and other analytical techniques in an attempt to find, identify and describe the material that is imparting magnetic properties to the tissue.

As far as vertebrates are concerned, a wide range have now been examined, and a distinct pattern is beginning to emerge. In several fish, including salmon and tuna, in the green turtle and, among mammals, in dolphins, mice and man (figure 4) magnetic deposits have been found localised in or near the organs of smell, particularly the region of the ethmoid or sphenoid sinuses. In humans these sinuses are on the mid-line between, behind and slightly below the eyes. In many vertebrates, though not yet in humans, this magnetic material has been confirmed to be magnetite. Excitement would be premature, but the possibility is being discussed that there may be an ancestral magnetoreceptor common to the vertebrates stock and based in some way on sinal deposits of magnetite.

As yet, the possibility that the sinus region plays a critical role in magnetoreception has not specifically been tested in behavioural experiments. The first indication that such evidence may soon be forthcoming has emerged from chair experiments on humans. Bar magnets (N pole uppermost; pole strength about 20 mT) near the sinus region for ten minutes lead to significantly worse compass orientation when the magnets are removed than do the same magnets on the back of the head. This 'after effect' seems to persist until the morning after exposure.

Whether the magnetoreceptor exists in the sinus region or elsewhere in the head, signals have to pass from the sense organ to the brain. Experiments by Peter Semm and his colleagues in Germany have shown, both for guinea pigs and homing pigeons, that nerves in the pineal body in the brain fire when the magnetic field changes. Perhaps, therefore, information from the magnetoreceptor passes to, or through, the pineal region of the brain.

The non-specialist reader of the more popular scientific press could be excused for assuming that, with the discovery of magnetite, the mechanism of magnetoreception by vertebrates has been all but explained. This is a good moment, therefore, to stress that for no animal is there critical behavioural evidence that magnetite is involved in magnetoreception. Having made this point, however, recent experiments on homing pigeons and humans are difficult to interpret except in terms of a magnetoreceptor based on magnetic particles.

Manipulating the particles?

Charles Walcott and James Gould in the USA have begun a series of experiments in which they expose homing pigeons to strong magnetic fields and then test the birds' performance in homing experiments. Some pigeons were exposed to an alternating magnetic field inside a set of Helmholtz coils arranged to null the earth's field. Field intensity began at a level 3000 times stronger than the earth's and was then slowly reduced. This was done three times on each pigeon, with the pigeon's head in different orientations each time. When such birds were released under sunny skies, they performed just as well as controls not exposed to the strong field. When released under overcast skies, however, they were at first disoriented and showed worse homing than controls.

It has been known for over a decade that, under sunny skies, experienced pigeons orient primarily by the sun. Under overcast skies, however, they orient instead by the earth's magnetic field. The implication of the results following exposure to a strong alternating field, therefore, is that the pigeons' health and performance had been unimpaired but their magnetic sense had been disrupted.

A second group of pigeons was exposed to a strong but steady magnetic field more than 2000 times stronger than the earth's by placing their heads between the pole pieces of a magnet. Again this had no effect on birds released under sunny skies but under overcast the treated birds seemed to be better oriented and homed faster than the controls.

Walcott and Gould interpreted their results as follows. Birds placed in an alternating field had their magnetic particles scrambled, different particles becoming oriented in different directions. Birds placed in a strong, steady field, however, had their particles aligned more uniformly than is naturally the case. The implication is that the more

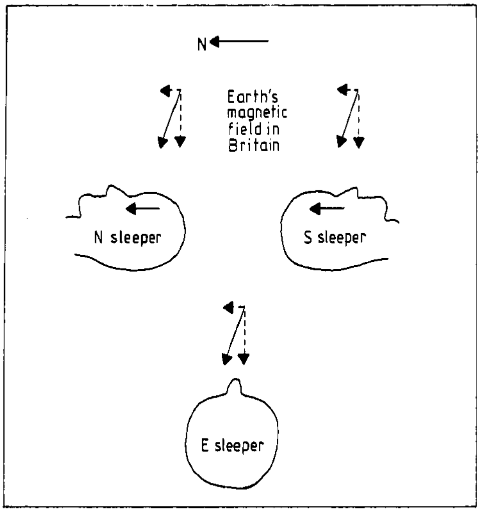


Figure 5 Assuming that people roll from side to side during the night and that the alignment of magnetic particles in the head can be influenced by the earth's magnetic field, the extent and polarity of alignment of the particles will vary from person to person and be a function of bed orientation

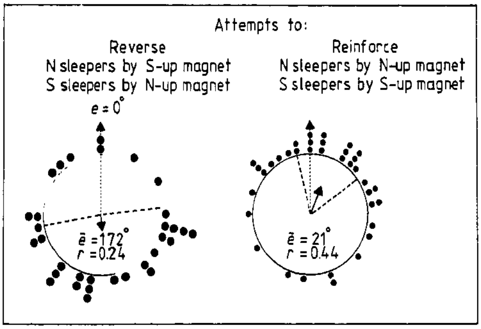
strongly aligned the particles, the more acute is the magnetic sense in judging direction.

This hypothesis, if true, could make sense of one of the more bizarre discoveries in the work on humans. Subjects who sleep on beds aligned along the N–S axis show a consistently better sense of direction than subjects who sleep on beds aligned along the E–W axis. It so happens that a N–S bed alignment would produce a better alignment of magnetic particles (figure 5) – as long as, over a period of about 8 h, the earth's magnetic field were strong enough to realign magnetic particles already present or to align particles being newly deposited overnight.

According to this hypothesis, people who sleep with their feet to the south (S sleepers) should, when they stand, normally have their particles aligned N pole uppermost, whereas the opposite should be true for people who sleep with their feet to the north (N sleepers). In which case, a strong bar magnet on the side of the head with the N pole uppermost should reverse the particles of S sleepers but reinforce alignment of the particles of N sleepers. Conversely, a magnet with S pole uppermost should reinforce S sleepers but reverse N sleepers. Experiments have been carried out in which blindfolded subjects, all N–S sleepers, have worn two bar magnets (pole strengths approximately 20 mT) one on each side of the head, either side of the ethmoid sinus (figure 2) for ten minutes. The magnets were then removed and the subject's ability to judge compass direction in the earth's magnetic field tested in the rotating chair. The results were almost exactly as predicted by the hypothesis. Estimates made by those whose particles should have been reversed are rotated by nearly 180° (figure 6). Moreover, not only are estimates by those who were reinforced significantly accurate but also more detailed analyses suggest performance is actually improved compared with controls not exposed to magnets before testing.

These experiments on homing pigeons and humans are both at an early stage. More individuals need to be tested and alternative explanations for the results should be sought and assessed. For the moment, however, the possibility that particles may be manipulated by applied fields and that the acuity of direction finding may be improved as well as disrupted must rank as a most exciting development. At the same time, of course, we may begin to wonder what short- and long-term effects there may be from any 'manipulations' brought about by the strong magnetic fields that are such a feature of our modern industrial environment.

Figure 6 Estimates of compass direction in 'chair' experiments suggest that attempts to use bar magnets to reinforce or reverse the alignment of particles in the heads of N–S sleepers have been successful. Each dot is the mean error of 9 estimates during a single test run by one person



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