

THE EFFECTS OF STATIC MAGNETIC FIELDS ON
DIRECTIONALITY IN HUMANS

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THE EFFECTS OF STATIC MAGNETIC FIELDS ON
DIRECTIONALITY IN HUMANS

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DISSERTATION ABSTRACT

THE EFFECTS OF STATIC MAGNETIC FIELDS ON
DIRECTIONALITY IN HUMANS

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Earth produces a dipole static magnetic field that is sufficiently stable to allow derivation of directional cues in a variety of species. This ability, known as magnetoreception, has been studied primarily in birds and reptiles, but some research has suggested that the ability exists in mammals. The present set of experiments was designed to investigate magnetoreception in human.

Three experiments are discussed in which participants were exposed to static magnetic field anomalies in a variety of contexts. In Experiment 1, participants were

taken to test locations and asked to indicate the location of a target. In Experiment 2, participants were required to guess which cardinal direction they faced while being rotated in a chair. In experiment 3, participants were required to discriminate between the presence and absence of a static magnetic field anomaly.

While results were mixed, Experiment 3 suggests that an ability to discriminate between the presence and absence of a magnetic field anomaly can be acquired over time. Theoretical implications and suggestions for further research are discussed.

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I. INTRODUCTION

Animals are able to *orient* (determination of direction) and *navigate* (travel through one's environment) through their environment. These generally involve multiple sensory modalities. While the contributions of the five most widely accepted senses (i.e. vision, olfaction, audition, gestation, and the skin senses) have been examined, another possibly more integral sense has received relatively little attention. *Magnetoreception* refers to an ability to detect magnetic fields and behave based on that information. Since Earth produces a static magnetic field whose dimensions vary subtly at different points on Earth's surface, it is reasonable to suspect that some organisms may possess mechanisms for magnetoreception. In fact, a relatively large body of behavioral evidence suggests that many species do use magnetic cues to orient and navigate.

Earth produces a dipole magnetic field that results in magnetic North and South poles. Earth's magnetic field is oval in shape and is generated at the poles. As a consequence, the angle of the field relative to Earth changes as a function of distance from the pole; the field is perpendicular to Earth at the poles and is parallel to Earth at the equator. The measure of the angle of Earth's magnetic fields relative to the surface of Earth is referred to as Earth's inclination. Earth's magnetic field also has a total and a local intensity. The local intensity varies at different points on Earth; it is strongest at the magnetic poles and weakest at the magnetic Equator, but the gradient of intensity does not follow a linear function. Thus, Earth's magnetic field is characterized by its

direction, angle relative to the surface of Earth, local intensity, and total intensity. Any or all of these characteristics may contribute to magnetoreception.

Even at the magnetic poles, the magnetic fields produced on the surface of Earth are relatively weak. Magnetic field strength is commonly measured in Gauss (G) or Tesla (mT) (1 mT = 10 G). Earth's magnetic field ranges from 0.028 mT to 0.06 mT, although an estimate of Earth's magnetic field of 0.5 G is usually accepted. The relative weakness of Earth's magnetic field can be demonstrated with a simple compass. If a compass is placed near electric or electronic devices (e.g. refrigerator, television, mobile telephone, computer, etc.), the compass will be disrupted. This disruption is an indication that the magnetic fields generated by these devices are more powerful than that of Earth.

The evidence for magnetoreception is abundant. Field examples of magnetoreception are common, although laboratory analogues have proven more elusive. Thus, most experiments have focused on demonstrations of magnetoreception rather than localization of the mechanisms underlying the process. Magnetoreception has been demonstrated in widely different species ranging from honeybees (Walker & Bitterman, 1989a) to humans (Baker, 1989b); however, most research in the area has involved birds. Birds are an ideal choice for research for several reasons. They can be inexpensive and reasonably easy to manage, but more importantly, the extravagant journeys made by birds during migration have long intrigued scientists. Migrating birds are the most appropriate choice for such experiments because of their demonstrated accuracy on long trips. Magnetoreception has been observed in a variety of birds including the European robin (Wiltschko & Wiltschko, 1972), blackcaps (Viehmann, 1979), pigeons (Beason Wiltschko & Wiltschko, 1997), and bobolinks (Beason, 1989).

Beason (1989) conducted one of the most convincing demonstrations of the effect of magnetic fields on navigation using adult bobolinks. Adult bobolinks were the ideal subjects for a study of magnetoreception because they have the longest migratory path of any New World land bird, and adult bobolinks presumably have experience with long-distance navigation. Testing was conducted in a planetarium in which seasonally appropriate stellar patterns were projected onto the planetarium dome. The magnetic field strength within the planetarium was approximately 90% of that of Earth, and the vertical component of the field was reversible using a pair of Helmholtz Coils. When magnetic information and stellar cues were consistent, all bobolinks, tested individually, flew in the seasonally appropriate direction. When stellar cues were reversed, three of ten bobolinks ignored the change in stellar cues and continued flying in their initial direction. Within four days, the remaining seven birds reestablished their initial flying direction and ignored stellar cues. Finally, the vertical component of the magnetic field was reversed and the stellar cues were returned to their appropriate position (reversal of the vertical component of the field results in a reversal in the field's inclination without reversing the field's polarity). Compared to the first condition in which stellar and magnetic cues were both in their appropriate state, the mean direction of flying was opposite when the vertical component of the field was reversed. This finding suggests that bobolinks use an 'inclination compass' derived from magnetic information for navigation and that stellar cues are used secondarily to magnetic cues. It is important to highlight the observations that the direction of flying was not uniform among all birds when the magnetic field was reversed, suggesting that a period of disorientation followed

the reversal. Furthermore, it took up to five nights for some birds to respond to the field reversal, although most responded within the first night.

Quentmeier (1989) both replicated and extended the findings of Beason using a virtually identical apparatus and methodology. Quentmeier reported increases in pigeon heart rate when the magnetic field was inverted and also noted that the maximum heart rate increase occurred several seconds after the field was inverted. Quentmeier also found that there were no differences in heart rate shift as a function of age, suggesting that perception of magnetic fields is either innate or learned very early in life. He also systematically varied the angle of the magnetic field vector in later trials and noted a significant increase in heart rate when the vector was oriented south-southeasterly, northerly, and south-southwesterly. Again, there were no differences in responding due to age of the pigeon.

Bookman (1977) reported perhaps the most successful laboratory demonstration of magnetoreception in birds and its relation to movement in homing pigeons (*Columbia livia*). The birds were trained to operantly discriminate between the presence and absence of an Earth-strength (0.5 G) magnetic field. A critical component of this experiment was the apparatus used for testing the pigeons. Previous studies failing to observe magnetoreception used Pavlovian and operant procedures that required the bird to be restrained from movement (e.g. Delius & Emmerton, 1978, Alsop, 1987). In contrast, Bookman's study used an operant chamber that consisted of a long flight chamber that allowed for voluntary movement and flight by the bird. The magnetic field was induced throughout the entire chamber, and two feeding boxes were located at the end of the chamber (one associated with the presence of a magnetic field, the other

associated with the absence of a magnetic field). During training, one of two strategies was observed in the pigeons: walking the length of the chamber and entering the feeding box or engaging in bursts of 'flutter' activity. Fluttering was defined as brief flights, jumping, sustained hovering, and rapid turning. Pigeons that engaged in 'flutter' activity correctly discriminated between fields (range = 76.4 - 82.0% correct) whereas those that did not engage in 'flutter' activity performed at random levels.

Bookman's (1977) findings are relevant for several reasons. First, they represent a controlled laboratory demonstration of operant discrimination of magnetic fields. Second, by providing an easy-to-replicate experimental paradigm, the Bookman study provides the foundation for identifying the mechanism(s) of magnetoreception. Finally, it suggests that self-initiated species-specific movement (rather than induced movement) may be necessary to activate the magnetoreceptive mechanism(s).

Importantly, some evidence suggests that magnetic fields are perceived even when pigeons are restrained (i.e. when species-specific movements are prevented). Hornung (1993) fixed pigeons to a wooden cradle and attached electrodes to the neck and rump to record electrocardiogram signals. The local magnetic field was altered by a set of Rubens coils attached to a Plexiglas chamber, and each pigeon was exposed to ten presentations of an inverted horizontal Earth-strength magnetic field, a control condition (normal Earth-strength field), and a shamfield control condition (the same heat and vibrations produced by activating the Rubens coils without the inversion of the horizontal field; this was accomplished by producing current that circles in opposite directions in each coil). Hornung reported the replicated finding that the implementation of the magnetic field inversion following a control or shamfield trial resulted in a significant,

albeit modest, increase in heart rate (mean heart rate per second was calculated, and only 4 of 20 one-second means were significantly higher than either control condition). Only 1 one-second mean was significantly different when the control condition was compared to the shamfield control condition. Hornung suggested that the small effect size was due to the fact that pigeons were differentially affected by exposure to the inverted field; some pigeons responded to the inversion, whereas other demonstrated no change in heart rate. An interesting finding of the study was that maximum heart rate acceleration did not occur until the sixth to eighth second of stimulus onset. This finding suggests that, similar to Beason's (1989) results, changes in magnetic fields are not perceived as abrupt shifts; rather, they are detected some time during stimulation. Hornung's study appears to contradict the observation that movement is necessary for magnetic field detection, although movement may enhance the perception of magnetic fields.

Several experiments have sought to alter navigational patterns by exposing birds to a strong magnetic field shortly before their journey. Such experiments have produced mixed results. Walcott, Gould, and Lednor (1988) briefly exposed pigeons to strong static and alternating fields prior to their journey and noted no deterioration in navigational performance. Conversely, Kiepenhaur, Ranvaud, and Maret (1986) exposed pigeons to 10 T static magnetic fields and noted significant shifts in navigational direction and increased scattering compared to control animals. Beason et al. (1997) suggested that the use of electromagnets may be responsible for discrepant findings. When current is applied to the electromagnets, the intensity of the field increases relatively slowly, taking up to several seconds to reach full intensity. The hypothesized

material responsible for magnetic orientation (magnetite, discussed later) may be able to temporarily align with the slowly increasing field without altering the magnetic axes.

Beason et al. (1997) attempted to disrupt magnetoreception by exposing pigeons to a 5 ms 0.5 T magnetic pulse. Since the magnetic material (magnetite) would not have sufficient time to align with the pulse before being remagnetized, the magnetization of the particles should have been altered. Pigeons were taken to release sites that were 40 to 170 km from the home site and exposed to the magnetic pulse, and each bird was released from multiple release sites. The exact duration between the magnetic pulse and first release was unreported. All releases occurred on sunny days so the pigeons' sun compass could still be used.

The primary measure of the effect of the magnetic pulse was vanishing bearing (the last place the bird was observed before disappearing over the horizon) observed by binoculars and measured with a compass to the nearest five degrees. The results were highly variable; sometimes there were strong differences between experimental and control pigeons, sometimes there was no difference at all. Significant differences between pigeons were seen mostly when the release site was more than 100 km from the home site. This effect suggests that different navigational mechanisms may be used by pigeons based on length of journey; however, the mechanisms responsible for determining length of journey are unclear. Furthermore, the magnetic pulse did not produce deflections in a reliable direction; some pigeons were deflected clockwise and others were deflected counterclockwise. Interestingly, when the same birds were released the following day without further exposure to the magnetic pulse, significant differences were again observed between experimental and control birds. This effect

dissipated by the third day. The most important contribution of the Beason et al. (1997) study is that it demonstrates the duration of the effect of a magnetic pulse. Because the magnetic pulse disrupted navigational abilities for two days even when the sun was present, one can conclude both that magnetic cues are extremely relevant and that those cues have long lasting effects.

Magnetoreception in Insects and Non-Mammalian Vertebrates

While the majority of magnetoreception studies used birds, some work has been conducted with other species. The honeybee in particular has received attention. Walker and Bitterman (1985) trained honeybees to discriminate between anomalies in the local magnetic field. Walker and Bitterman (1989a) also trained honeybees to discriminate between the presence and absence of a magnetic field anomaly. All honeybees were found to reliably discriminate between the presence and absence of a static magnetic field at 1 μT (microTesla = one millionth of a Tesla) and some honeybees were able to perform the discrimination below 0.1 μT .

Kirschvink, Padmanabha, Boyce, and Oglesby (1997) investigated the sensitivity of the honeybee to alternating current (A.C.) magnetic fields. This experiment improved the apparatus used by Walker and Bitterman (1989a, 1989b) by using an automated system to deliver reinforcement, thus eliminating odor cues that may have been relevant during the discrimination. That is, unlike the Walker and Bitterman studies, a sucrose solution was not placed in the feeding tube until *after* a choice was made. Honeybees were required to select one of two feeding tubes based on the presence or absence of an A.C. magnetic field; correct choices were reinforced with a sucrose solution and incorrect choices were punished with tap water and an electrical shock. Honeybees were tested

with either a 60 Hz or 10 Hz A.C. magnetic field. The field intensity began at 1300 μT and was reduced when reliable discrimination was demonstrated. These reductions continued until the honeybees showed no further discrimination. At 10 and 60 Hz, most bees were able to discriminate between the presence and absence of a 1300 μT field. However, as the strength of the field was reduced, the frequency of the field had a strong impact on the discrimination. At 60 Hz, the weakest field discrimination made by any bee was 430 μT . In contrast, at 10 Hz, the weakest field discrimination made by any bee was 1.3 μT . Thus, there is a trade off between frequency and strength in magnetic field discriminations by honeybees.

Walker and Bitterman (1989a) found that all bees tested could discriminate between the presence and absence of static magnetic fields as low as 1 μT , while Kirschvink et al.'s (1997) results suggest a significant deterioration of magnetic discrimination skills when the field was generated using alternating current. These findings are consistent with the evolution of magnetoreception. Honeybees (or any other organisms) were not exposed to alternating current prior to the human electrification of Earth; thus, magnetoreception evolved in response to static magnetic fields rather than alternating currents. While detection of A.C. fields may seem irrelevant in a natural setting (after all, Earth produces a *static* field), such a capacity may become increasingly relevant. Power lines produce A.C. current, and their presence may disrupt the navigational and even migratory patterns of organisms that rely on magnetic information.

Phillips and Adler (1978) demonstrated discrimination of static magnetic fields by cave salamanders (*Eurycea lucifuga*) in a pseudo-natural environment. Two groups of salamanders were released into the center of a darkened, elongated tube apparatus. The

apparatus used by salamanders in Group A was enclosed in electromagnetic coils that produced an Earth-strength magnetic field that was rotated 90 degrees and Group B was exposed to Earth's normal magnetic field. Thus, each group could move in one of two directions during training. Limestone and moisture, natural reinforcers for the cave salamander, were alternately placed at the end of one arm of the corridor for each group during each day of training. The purpose of this training was to encourage the salamanders to explore both arms of the apparatus. For Group A, the north-south axis of the magnetic field was perpendicular to the salamander's movement. For Group B, the north-south axis was parallel to the salamanders' movement. During testing, all salamanders were placed in a darkened cross-shaped apparatus that generated a normal Earth-strength magnetic field and were allowed to move about for forty minutes. Their position after forty minutes, either parallel or perpendicular to the magnetic field, was recorded. Significant differences between group A and B were observed in six of sixteen tests, suggesting that the groups adopted different strategies for navigation. In tests where significant differences were recorded, the majority of salamanders moved in the appropriate direction with respect to training (i.e. Group A moved perpendicular to the field and Group B moved parallel to the field).

While the Phillips and Adler (1978) study provides some evidence of magnetoreception by salamanders, their results are difficult to interpret on several grounds. First, the fact that significant differences were observed on less than half of the tests is problematic. It is possible that salamanders require more training with an altered field to make reliable discriminations. It is also possible that, unlike pigeons, salamanders process elements of a magnetic field separately (i.e. process polarity and

inclination separately rather than processing the whole vector). Phillips and Adler provide no information about the inclination of the fields in training or testing, so this latter hypothesis cannot be analyzed. More problematic, the magnetic coils may have produced heat or vibration that acted as a cue for Group A during testing. This manipulation may explain why, on some tests, the majority of salamanders in Group A moved in the opposite direction learned in training, a reversal that did not occur on any test trials with Group B. Most importantly, salamanders in Group A were exposed to a 90 degree switch in the magnetic field between training and testing. No attempt was made to control for the switch (i.e. housing salamanders in Group B in an apparatus that produced a magnetic field that was perpendicular to Earth's magnetic field). The Phillips and Adler study represents the most sophisticated and refined application of this apparatus and procedure using salamanders (for earlier applications, see Phillips, 1977), but because of these problems, the demonstration of magnetoreception in cave salamanders remains tentative.

Phillips (1986a) more effectively demonstrated magnetoreceptive navigation in another amphibian, the red-spotted newt (*Notophthalmus viridescens*). Newts were placed in a pool that varied in temperature between 17 and 27° C. During testing, the temperature in the pool was raised to 32° C and newts uniformly moved shoreward. Shoreward movement is a common response by salamanders when water temperature is raised. When the vertical component of the ambient magnetic field was inverted, newts moved in the appropriate direction as indicated by the magnetic field (as previously stated, the inversion of the vertical component reverses the field's inclination without reversing the polarity). This finding suggests newts use an 'inclination compass' similar

to that used by pigeons. Nonetheless, when the direction of magnetic north was shifted, newts' direction of navigation shifted accordingly, suggesting that newts respond to both changes in inclination and angular shifts in polarity direction. Phillips noted that when newts were homing they responded to the field's horizontal polarity, but when they engaged in simple compass orientation they responded to the field's inclination. This finding suggests that newts have multiple magnetoreception pathways or mechanisms (Phillips, 1986b).

Magnetoreception has been demonstrated in a host of aquatic animals including sharks and rays (Kamijn, 1982), sockeye salmon (Quinn, 1980), and sea turtles (Goff, Salmon, & Lohmann, 1998). Similar to birds and bees, discrimination between magnetic fields has been demonstrated in the laboratory in at least one species of fish. Walker (1984) designed an apparatus for testing yellowfin tuna that was analogous to Bookman's (1977) apparatus for testing pigeons. The apparatus consisted of a round fish tank (1 m in depth, 6 m in diameter) wrapped in AWG magnet wire to induce artificial vertical magnetic fields within the tank.

In Walker's experiment, tuna were reinforced with food for swimming through a pipe frame when one magnetic field was present and were not reinforced for swimming through the pipe frame when the inverted field was present. For some fish, the ambient field was the discriminative stimulus associated with reinforcement and for others the inverted field was the discriminative stimulus associated with reinforcement. Since a double-blind discrete-trials/fixed-interval schedule was employed, the presence of the reinforcer or experimenter's behavior could not have acted as a cue for responding. By the third training session, all fish responded at higher levels during reinforced trials than

during unreinforced trial. As a control condition, one of the trained fish was tested in the apparatus, but the wires connecting the power supply to the coils were disconnected. In this condition, there was no significant difference in responding between reinforced and non-reinforced trials. When the wire was reconnected, the higher rate of responding to the reinforced stimulus resumed.

Interestingly, preliminary studies indicated that exposure of yellowfin tuna to a momentary magnetic field anomaly (no information on the duration, strength, or inclination of the field was provided) resulted in a delay in swimming through a tunnel that had previously been associated with reinforcement. This finding alone is of interest, because it indicates that yellowfin tuna perceive changes in magnetic fields when they occur. Previous work with pigeons has suggested that magnetic fields are perceived gradually rather than immediately (Beason, 1989); thus, the magnetoreceptive mechanism of yellowfin tuna may be more finely tuned to shifts in magnetic fields or may be qualitatively different than that of pigeons.

In a separate study, Walker (1984) exposed yellowfin tuna to two different magnetic fields, neither of which corresponded to the natural ambient field in the tunas' home environment. The two fish tested were unable to acquire a reliable discrimination between the two fields. This may have occurred for two reasons. Beason et al. (1997) demonstrated that exposure to magnetic fields can affect responding long after the field has been discontinued. Following this logic, the tuna may have actually been required to discriminate between three magnetic fields rather than two, the third being the persistence of the natural ambient field. Such discrimination may not be possible by yellowfin tuna or may require more extensive training. Similarly, exposure to two novel fields

following a relatively long exposure to the natural ambient field may cause a period of disorientation. Disorientation was observed in pigeons when they were exposed to a brief magnetic pulse after being housed in the natural ambient field (Beason et al., 1997). It is important to note that both the angle of inclination and strength of the field (along with gradients in intensity and inclination) were altered; therefore it is not possible to assess what, if any, *elements* of the field were actually perceived by the fish.

Magnetoreception in Mammals

Magnetoreception has been demonstrated in several species of mammals including humans (Baker, 1981), horses (Baker, 1989a), and various species of rodents (Deutschlander et al., 2003; Mather & Baker, 1981). Mammalian magnetoreception, however, remains controversial. For instance, Mather and Baker (1981) reported that an ambient magnetic field reversal caused European woodmice to home in the opposite direction relative to the normal ambient field, but Sauve (1985; as cited in Deutschlander et al., 2003) was unable to find evidence for homing in woodmice using a similar experimental procedure. Many discrepancies in results of experiments using mammals can be attributed to differences in experimental design and apparatus; unlike birds, for whom there is a large body of research for individual species, there is little research on the magnetic sense of any single species of mammal. Because of the lack of research, there are no standards for experimental design. Most studies of magnetoreception in mammals have focused on rodents, but unlike the operant procedures used to test some birds and fish, rodent studies have mostly examined nest and food cache displacement in response to changes in the ambient magnetic field.

Burda, Marhold, Westenberger, Wiltschko and Wiltschko (1990) demonstrated magnetic compass orientation in blind mole rats (see Kimchi and Terkel, 2001, for an independent replication). Beason (1989) and others have demonstrated the redundancy of sensory systems in providing navigational information and, since mole rats are blind, it is possible that they have a hyper-developed magnetoreception system.

Deutschlander et al. (2001) performed nest displacement studies with Siberian hamsters to determine whether visual rodents also exploit magnetic information for navigation. Experiments were conducted in a diffusely lit circular arena, and mated pairs of hamsters were used as subjects to closely approximate studies with mole rats. Each pair of hamsters was tested under four alignments of a static magnetic field. When no alteration in the ambient field was present, hamsters built nests located on an axis of 118-298 degrees, but no preference for one end of the axis was observed. When other magnetic fields were present, nest location was random. Thus, the magnetic shift resulted in a change in nesting behavior; however, magnetic shifts did not produce reliable shifts in nesting.

In a second experiment, individual hamsters housed in a separate building were tested. Two groups were used: hamsters in Group A were housed in cages positioned on a 45-225 degree axis prior to testing while hamsters in Group B were housed on a 135-315 degree axis. When individual hamsters were tested in the circular arena, hamsters in Group A built their nests on an axis significantly different from those in Group B. When nest locations were pooled without respect to the alignment of housing cages, nest building appeared to be randomized (Deutschlander et al., 2001). This finding highlights one of the major difficulties in probing for magnetoreception and, more importantly,

making predictions about behavioral change based on magnetic manipulations: the previous magnetic experiences of organisms in a natural setting and in the laboratory influence behavior even after the magnetic stimulus has been removed. Unlike visual, auditory, or olfactory cues, eliminating magnetic stimuli is often costly and impractical, and eliminating magnetic cues entirely prior to testing may produce unpredictable responding. Furthermore, the duration of the effect after the field has been removed is unknown and may vary substantially between and within species.

Research using human subjects has focused on the effects of magnetic field manipulation on displacement rather than discrimination of magnetic fields. Three types of magnetoreception experiments have been conducted with humans: bus experiments, walkabout experiments, and chair experiments. In bus experiments groups of subjects are blindfolded, driven to a distant location, and asked to indicate the direction of home (or the test site relative to home). In walkabout experiments, groups of subjects are taken on walks in unfamiliar wooded areas and are asked to indicate the direction of home. The obvious disadvantage of this type of experiment is that navigational cues derived from different sensory modalities may interfere or interact with a magnetic sense and produce data that are difficult to interpret. Bus experiments improve on this flaw only slightly by eliminating visual cues.

Chair experiments permit better interpretations by allowing better experimental control. They are performed in a laboratory where both auditory and visual cues are eliminated by earmuffs and a blindfold, respectively. Subjects are placed in a rotating chair and, after several gentle rotations in both directions, asked to verbally estimate their current compass. While chair experiments control for many confounds of other research

types, they have the disadvantage of preventing the species-specific movements that may be necessary to activate navigational mechanisms. In all three types of experiments, an experimental group of subjects is exposed to an alteration of Earth's magnetic field and is compared to a control group. Using different apparatuses to deliver the magnetic field, Baker has reported both displacement and no effect in humans (Baker, 1989b).

Baker (1980) first suggested that human navigation may involve a magnetic sense. Baker blindfolded small groups of college students and drove them between 6 and 52 km from their university. Subjects were instructed not to speak to each other and the journey was sufficiently elaborate to prohibit navigational information from being derived by counting turns. Upon reaching their destination, subjects were removed from the vehicle, still blindfolded, and asked to state the compass direction of the test site from the university. A mean vector of the estimates was calculated for release sites (release sites were grouped based on their compass direction from the university) and, regardless of direction or length of journey, participants were able to accurately predict the direction of home. The mean vectors ranged from 1 to 44 degrees from the true direction depending on the direction of the test site and most individual estimates were within 45 degrees of the true direction. When subjects were asked how they made their compass estimates, they were unable to describe the mechanism used to determine direction.

Baker later replicated the experiment, but before the experiment began, he placed bar magnets on the backs of experimental subjects' heads and non-ferrous brass bars of equal size in the same position on the heads of control subjects. Control subjects demonstrated accuracy in their judgments of direction, but experimental subjects did not.

While control subjects' estimates were clustered around the home direction, experimental subjects' estimates were completely random.

Unfortunately, conclusions about the effects of magnetic fields on navigation in humans cannot be derived from Baker's (1980) study for several reasons. First, Able and Gergits (1985) were unable to replicate the finding that untreated participants can accurately estimate the direction of a home location; thus, Baker's (1980) interpretations of the effects of magnetic fields on orientation may be misguided. Second, the position of the magnets on the subjects' head could not be standardized (the magnets could move around during the journey) and the bar magnets were not of uniform strength. Furthermore, control and experimental subjects were not separated during the journey; thus it is possible (albeit highly unlikely) that control subjects were somehow influenced by experimental subjects. However, Baker's study provided the impetus for further studies of magnetic field detection in humans.

Using the walkabout methodology, Baker (1989b) found that untreated subjects taken on walks across unfamiliar, wooded areas were able to estimate the home direction more accurately than if they had guessed. If subjects had guessed, home estimates should have been equally distributed across all directions; rather, home estimates were localized around the actual direction of home. Subjects' estimates were more accurate at day than at night and more accurate during clear days than when there was cloud cover, suggesting that sun cues influenced estimates of compass direction. Subjects with bar magnets attached to their heads were influenced by the presence of magnets even when the sun was shining, although sometimes the magnets reduced accuracy and sometimes they increased accuracy. The somewhat contradictory results highlight the walkabout

methodology's primary flaw: we poorly understand the mechanics of any navigational system in humans; thus, the interaction of multiple navigational systems is virtually impossible to interpret. Baker attempts to explain the phenomenon with reference to the effect of cloud cover on displacement, but without a better understanding of the mechanics of magnetoreception, any interpretations are speculative.

The best evidence for a magnetic sense in humans comes from chair experiments. Brian conducted a double-blind study in which blindfolded, earmuffed subjects were placed in a chair surrounded by large, stationary electromagnetic coils that produced a static magnetic field throughout their entire body. Subjects were exposed to fields with inclination unchanged, inclination reversed, or no inclination. Each subject was tested on twenty different occasions with only one of the fields present, and at least 5 days elapsed between each test. In the normal field, estimates of north by nearly all subjects clustered around geomagnetic north. When the field's inclination was reversed, estimates of north reversed. When the field's inclination was eliminated, compass orientation deteriorated to random levels (Baker, 1989b).

Baker performed a similar experiment using electromagnetic coils that changed the magnetic field only in the head and upper torso of subjects. He also found that reversing the magnetic field was associated with a reversal in the mean vector of directional estimates, although Baker observed far more between-subjects variability. Such variability may have been due to head and torso exposure to the magnetic field, but it is equally likely that the variability is the result of the duration of the experiment; whereas Brian tested each subject twenty times, Baker tested each subject only twice

(Baker, 1989b). Unfortunately, Kirschvink, Jones, and MacFadden (1985) were unable to replicate Brian and Baker's (1989b) findings using a similar methodology.

Murphy (1989), using the chair procedure, produced the most revealing results regarding the development of human magnetoreception. Nearly 1300 subjects were tested ranging in age from four to twenty. Subjects were first placed in the chair and turned to the four cardinal points (N, E, S, and W). An object was aligned at each cardinal point so children could describe their location by identifying the object. Subjects were then blindfolded and earmuffs were put on, and each subject was again turned around in the chair and told what object he or she was facing.

In the first experiment, all subjects had a brass bar in a paper bag placed on the right temple just behind the eye. The brass bar served a control function, since later testing involved placement of a bar magnet on the right temple. During testing, the chair was turned clockwise and counterclockwise and was stopped at a random position. Subjects were then asked to describe where they faced in relation to the objects. Results suggested that the performance of females but not males increased as a function of age, although 15-16 year old females performed better than 18-19 year old females. When divided by age and sex, females between the ages of 9 and 18 exhibited an ability to judge direction, whereas only males between the ages of 13 and 14 exhibited this ability. The performance of males and females rapidly deteriorated over the first several trials, suggesting that both groups initially attempted to follow the turns of the chair to make a decision. As the session progressed, females switched to an alternate strategy as indicated by improved performance in later trials. Thus, it is not clear whether males and

females are differentially prepared to detect magnetic fields or if females simply recognized that their initial strategy did not work and moved to another strategy.

Because 11-18 year old females demonstrated the best ability to judge compass direction, a separate group of female subjects in this age range was selected for magnetic manipulation experiments. The experimental design was identical to the first except that a brass bar was attached to the temple of some subjects and a bar magnet was attached to others. Approximately half of the magnets were placed north-up and half were placed south-up. Again, control subjects were able to reliably estimate their direction, but judgments by magnet-wearers were random. Curiously, no comparisons of north-up and south-up were included; thus, it is not possible to assess if exposure to a particular field resulted in a uniform displacement of directional estimates. Murphy (1989) noted that while the bar magnet immediately disrupted directional estimates, the disruption did not reach significance until the sixth trial (approximately four minutes after the magnet was placed on the subject). This finding is consistent with Beason's (1989) finding that a magnetic field reversal results in a delayed response to the new field. Murphy's (1989) study contrasts with Bookman's (1977) finding that pigeons must engage in particular self-initiated movements to activate the magnetoreceptive system; unlike Bookman's study, all movement was induced by the experimenter. It is possible that certain movements made by humans could further enhance magnetoreception, although that possibility has not yet been explored. While not explicitly stated, it is assumed that participants in Murphy's study were not restrained from making head movements in the experimental apparatus.

While there is an abundance of evidence in support of magnetoreception, many of the crucial experiments in the area have yet to be replicated. Especially among humans, the presence of such a sense remains controversial. While some experiments have suggested the existence of human magnetoreception (i.e. Baker, 1980; Murphy, 1989) others have failed to support these findings (i.e. Kirschvink, Jones, and MacFadden, 1985). It is possible that failures to observe magnetoreception in humans are due to humans' weak magnetic sense; certain preparations may be more conducive to observing magnetoreception in humans.

Magnetoreception may be weak in humans for several reasons. Through the forces of evolution, the sense may be disappearing in humans due to its lack of adaptive advantage. Alternatively, the sense may play a major role in navigation while remaining an entirely unconscious process. This seems likely, since human subjects who have demonstrated the sense have reported no unique sensations associated with it (Murphy, 1989). Most importantly, the electrification of most human environments has meant that humans spend a substantial period of time in altered magnetic fields. Power lines, electrical devices, and ferrous material in our environment may be sufficient to disrupt magnetoreception, although the behavioral effects and duration of the disruption are entirely unclear. Baker's (1981) demonstrations that bar magnets disrupt the magnetic sense give credence to the latter suggestion, and Kirschvink et al.'s (1997) demonstration that the magnetic sense of the honeybee is disrupted by A.C. fields provides an analogue to the human environment.

The present series of experiments were designed to determine if and under what conditions humans can use magnetic cues. The first two experiments represent

independent replications of previous experiments involving human magnetoreception.

Experiment 1 reexamines Baker's (1980) finding that humans can indicate the direction of a target location when taken to a test location while blindfolded and that bar magnets placed on the temples disrupt that ability. To increase experimental control in our replication, participants were blindfolded *and* were required to wear earplugs.

Additionally, participants were tested at only two test sites. Baker reported that estimates of the target location were unaffected by the direction or distance of the test location from the target location.

Experiment 2 reexamines Murphy's (1989) finding that, when auditory and visual cues are eliminated, humans could accurately indicate the direction they face.

Participants were seated in a chair and were blindfolded and wore earplugs.

Experimental participants had bar magnets fixed to their temples whereas control participants had non-ferrous brass bars fixed to their temples. The experimenter rotated the chair to a random position and asked participants to indicate which direction they were facing.

Experiment 3 sought to determine if humans could discriminate between magnetic fields produced by electromagnets. In Experiment 3, participants were required to discriminate between the presence and absence of a magnetic field that differed from that of Earth in intensity, polarity, and inclination.

II. EXPERIMENT 1

Baker (1980) found that humans are able to reliably indicate their homeward direction when taken to a novel location. He blindfolded participants and drove them to a location several miles from the home site, taking a sufficiently elaborate route that involved broad curves and overlapping of the path to eliminate any movement-related directional cues. Baker found that all participants indicated the homeward direction within 45 degrees of the actual home location. Another group of participants received identical treatment except small bar magnets were attached to the temple of the participants. In this condition, homeward estimations were completely random. The ability of participants to correctly indicate the homeward direction and the subsequent finding that bar magnets disrupted that ability were taken as evidence that humans can rely on a magnetic sense (magnetoreception) for directional judgments.

Aside from Baker, no researchers have attempted to replicate this finding. In order to establish the existence of a magnetic sense, Experiment 1 was a replication of the Baker (1980) study.

Method

Participants

Seventy-two Auburn University undergraduates were selected as participants in the experiment. Forty-seven of the participants were female and 25 were male.

Participants were instructed to remove all metal jewelry prior to testing. All participants were free of any metallic surgical implants.

Participants were randomly assigned to a sensory-block (SB) group or a no-sensory-block (NSB) group. Once assigned to either the sensory-block or no-sensory-block conditions, participants were randomly assigned to either a magnet-wearing (treatment) group or a brass-wearing (control) group. Participants were tested at one of two test sites, thus a total of eight groups were used.

Due to unplanned construction at the university, the experiment was discontinued before all data could be collected. As a result, number of participants per group and sexual makeup in each group varied. Group NSB-B-1 (no-sensory-block/brass/site 1) consisted of nine participants (six females, three males). Group NSB-M-1 (no-sensory-block/magnet/site 1) consisted of nine participants (five females, four males). Group SB-B-1 (sensory-block/brass/site 1) consisted of ten participants (eight females, two males). Group SB-M-1 (sensory-block/magnet/site 1) consisted of eleven participants (six females, five males). Group NSB-B-2 (no-sensory-block/brass/site 2) consisted of nine participants (seven females, two males). Group NSB-M-2 (no-sensory-block/magnet/site 2) consisted of nine participants (five females, four males). Group SB-B-2 (sensory-block/brass/site 2) consisted of six participants (three females, three males). Group SB-M-2 (sensory-block/magnet/site 2) consisted of nine participants (six females, three males).

Materials

Participants were required to wear light-shielding goggles and earplugs. The goggles used were commercially produced welding goggles. The goggles were

adjustable and were fitted to each participant's head. The lenses of the goggles were painted black with at least two coats of enamel paint. Each mask was checked by the experimenter to ensure that no light was visible during the daytime. Each participant wore disposable soft-foam earplugs that were designed to block up to 34dB. A 1996 Mazda Protégé was used to transport participants from Haley Center to the test locations. Additionally, a pair of Motorola two-way radios was used to maintain contact between the driver and the experimenter in Thach Hall.

A round, laminated board 24" in diameter was used to code participants' responses. Participants stood on the board while making directional estimates. Responses were then recorded in one of twenty-four zones. Each zone was 15°, and participants' responses were recorded on an analogous directional estimate recording sheet (see Figure 1). The estimate recording sheet contained a round figure divided into 24 zones. Each zone was 15°, and participants' responses were recorded by placing a check in one of the zones. Because the experiment involved a double-blind procedure, information regarding which participants wore magnets was recorded by a second experimenter in Thach Hall.

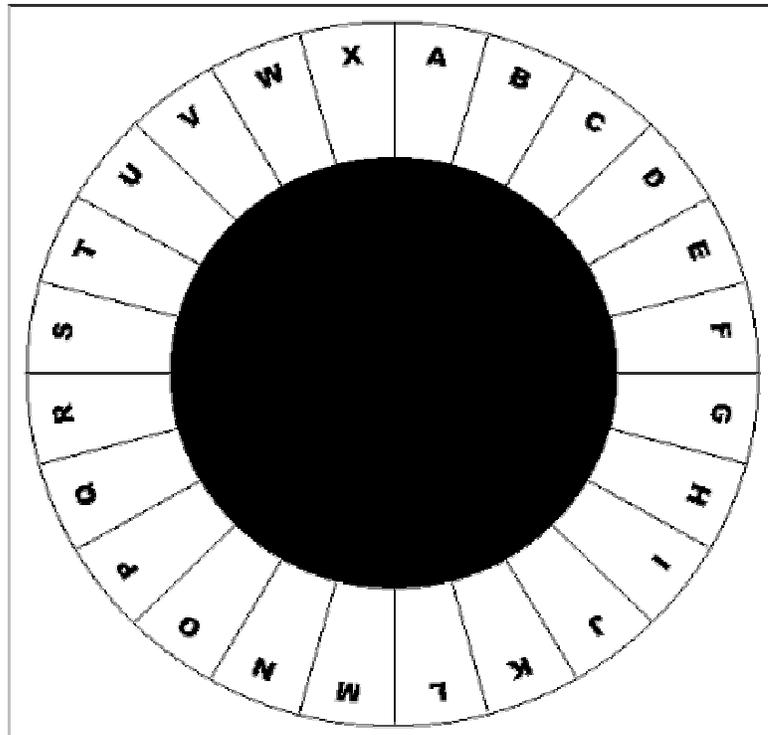


Figure 1

Recording tool for outdoors directional estimates experiment.

Commercially-available round magnets or non-ferrous brass buttons of similar height and weight were attached to each participant's head using an elastic headband made for the purpose of this experiment. Each headband contained six 1"x1" elastic pockets which held the magnets on brass buttons. The headband was fastened to each participant's head with a Velcro strip located at the end of each headband.

Procedure

Undergraduates were recruited and randomly assigned one of eight groups (*see Participants*) to reflect all possible combinations of sensory blockage (sensory-block vs. no-sensory-block), artificial magnetic field exposure (round magnets vs. non-ferrous

brass buttons), and site of testing (site 1 vs. site 2). Sensory blockage consisted of wearing light-shielding goggles and foam earplugs.

Participants met one of the experimenters in the basement of Thach Hall. After reading and signing an informed consent form, participants were led to the back entrance of Haley Center where another experimenter waited with the car. Participants were tested in groups of two or three. Each participant was seated in the car and was instructed to buckle his or her seatbelt. For sensory-block groups, the driver gave each participant foam earplugs and demonstrated how to correctly insert the earplugs. Participants were then instructed to insert their earplugs. The painted welding goggles were then placed on each participant. Once properly affixed, the experimenter asked (loudly) if participants could see any light. Goggles were readjusted if participants indicated that they could see light. All participants were fitted with an elastic headband that contained either round magnets or non-ferrous brass buttons. Participants were instructed to remain silent for the duration of the experiment. Once visual and auditory cues were blocked and the elastic headbands were affixed to the head, the participants were driven to one of two test locations (see Figure 2) at no more than 30 miles per hour. Each trip to the test location lasted approximately five minutes in duration.

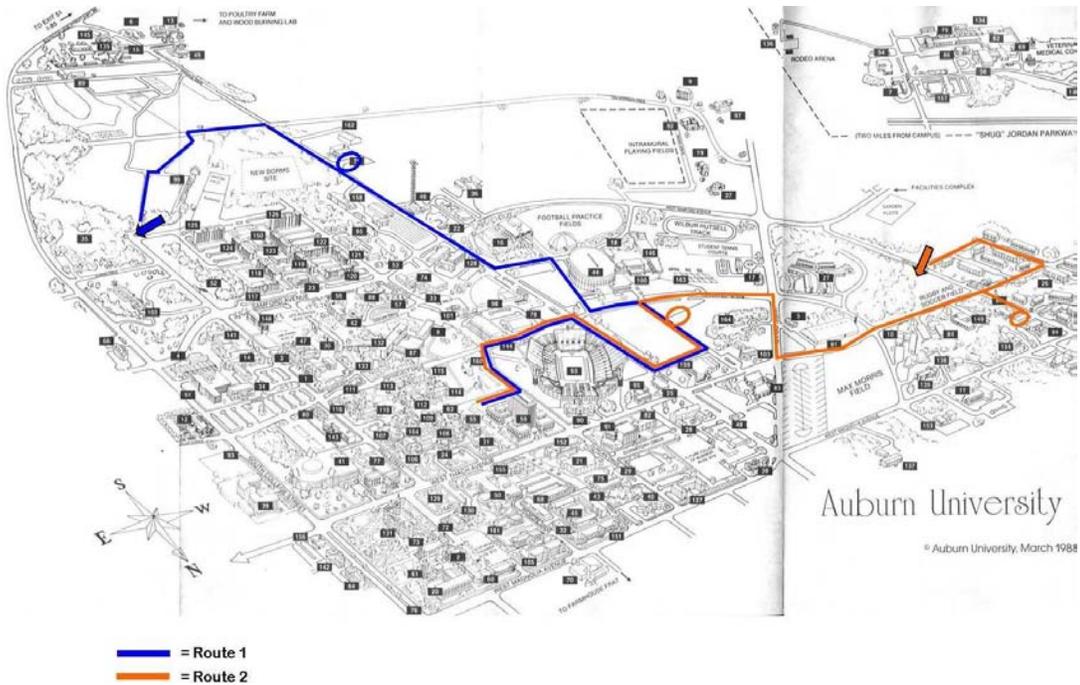


Figure 2

Test locations for outdoors directional estimates experiment.

Once at the test location, the driver instructed the participants to remain seated until they were instructed otherwise. The experimenter then set up the direction board and used a compass to ensure that the line separating the X and A zones pointed north. When the direction board was properly aligned, the experimenter led each participant to the board individually. While standing in the black area of the direction board, participants were slowly rotated clockwise between 540° and 720° until they faced the north-pointing line. Once facing north, the experimenter advised the participants that Haley Center could be located in any direction. Participants were then asked to point in the direction of Haley Center. After each participant made his or her estimate, they were instructed to remove their goggles and earplugs and be seated in the car. Participants

were again advised to refrain from communicating with the other participants until all participants made their directional estimate. After all participants made their estimates, they were returned to Haley Center and instructed to return to the basement of Thach Hall to get their belongings and extra credit.

Results and Discussion

Mean vector was calculated for each group via the circular statistics program Oriana 2.0. Unlike a linear mean, mean vector has the following properties: direction (μ) reflects the mean angle of directional estimates and vector length (r) reflects clustering around the mean direction. Vector length can range from zero to one, with higher values representing more clustering around the mean. Each group mean vector was compared to the actual target vector using a V-test to determine if the vectors differed significantly from each other. The V-test is a variant of the Rayleigh test that allows the user to specify the actual vector direction. The V-test tests against an alternative hypothesis that there is a non-uniform distribution. Thus, a statistically significant effect indicates non-uniformity or clustering in the distribution. A Watson-Williams F-test was used to compare mean vectors between groups. Mean vectors were not compared between sites.

Site 1

Each of the four groups' distributions were compared against the actual vector direction of the target (82.5°) using a V-test. Participants in Group NSB-B-1 demonstrated an ability to estimate the direction of the target ($\mu = 99.089^\circ$, $r = 0.967$). This was confirmed with a V-test, $V = 0.926$, $p < .001$. Participants in Group NSB-M-1 also demonstrated an ability to estimate the direction of the target ($\mu = 93.834^\circ$, $r = 0.889$) as confirmed by a V-test, $V = 0.882$, $p < .001$. Participants in both sensory-block groups

at Site 1 failed to accurately estimate the direction of the target. Participants in Group SB-B-1 produced a mean vector of 129.051° ($r = 0.092$) which differed significantly from the target's direction as evidenced by a V-test, $V = 0.063$, $p = .39$. Participants in the Group SB-M-1 produced a mean vector of 224.674° ($r = 0.417$) which differed significantly from the target's direction as evidenced by a V-test, $V = -0.33$, $p = .938$. (see Figure 3)

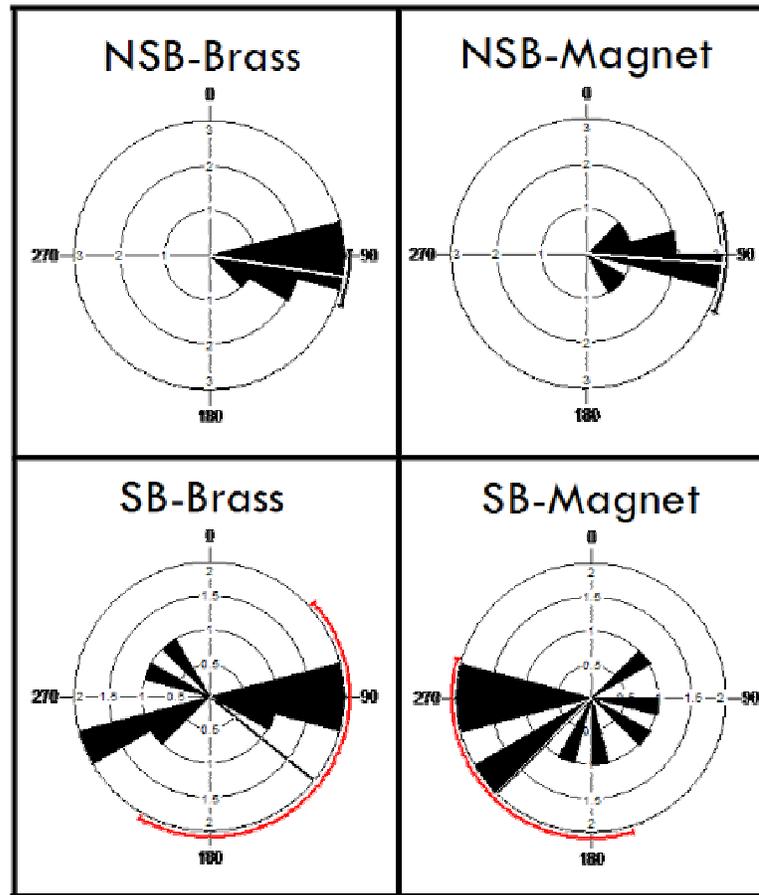


Figure 3

Distribution of directional estimates at Site 1.

Each mean vector was compared to the other mean vectors using a Watson-Williams F-test. Only two significant differences were observed. The mean vectors of

Groups NSB-B-1 and SB-M-1 differed significantly ($F = 20.075$, $p < .001$), and the mean vectors of Groups NSB-M-1 and SB-M-1 differed significantly ($F = 19.67$, $p < .001$). In the absence of sensory blockage, the presence of magnets did not affect directional estimates ($F = 0.245$, $p = 0.267$). Likewise, when auditory and visual cues were blocked, the presence of magnets did not affect directional estimates ($F = 1.906$, $p = 0.183$).

It is clear from participants' self reports that during no-sensory-block conditions, visual cues were used primarily for making directional estimates. Specifically, most participants indicated that very tall stadium lights located next to the target location were used to estimate the direction of the target. Most participants in sensory block conditions indicated that their estimates were guesses that were not based on any conscious experiences. The observation that Group SB-M-1 differed significantly from both NSB groups, whereas Group SB-B-1 did not differ from either NSB group, suggests that in the absence of visual and auditory cues the presence of magnets on the head may subtly influence directionality. This is further supported by the observation that the estimates of participants in Group SB-M-1 are more clustered ($r = 0.417$) than the estimates of participants in Group SB-B-1 ($r = 0.092$). Thus, in the absence of auditory and visual cues, the magnetic fields produced by Earth are insufficient as directional cues. However, the presence of much stronger magnetic fields such as those produced by the round magnets may provide some directional cues that are responsible for the clustering observed in Group SB-M-1.

Site 2

Each of the four groups' distributions were compared against the actual vector direction of the target (352.5°) using a V-test. Group NSB-B-2 demonstrated an ability to

estimate the direction of the target ($\mu = 324.364^\circ$, $r = 0.944$). This was confirmed with a V-test, $V = 0.833$, $p < .001$. Participants in Group NSB-M-2 also demonstrated an ability to estimate the direction of the target ($\mu = 328.06^\circ$, $r = 0.89$) as confirmed by a V-test, $V = 0.811$, $p < .001$. Participants in both sensory-block groups at Site 2 failed to accurately estimate the direction of the target. Participants in Group SB-B-2 produced a mean vector of 80.345° ($r = 0.918$) which differed significantly from the target's direction as evidenced by a V-test, $V = 0.035$, $p = .454$. Participants in the Group SB-M-2 produced a mean vector of 111.141° ($r = 0.325$) which differed significantly from the target's direction as evidenced by a V-test, $V = -0.156$, $p = .742$ (see Figure 4).

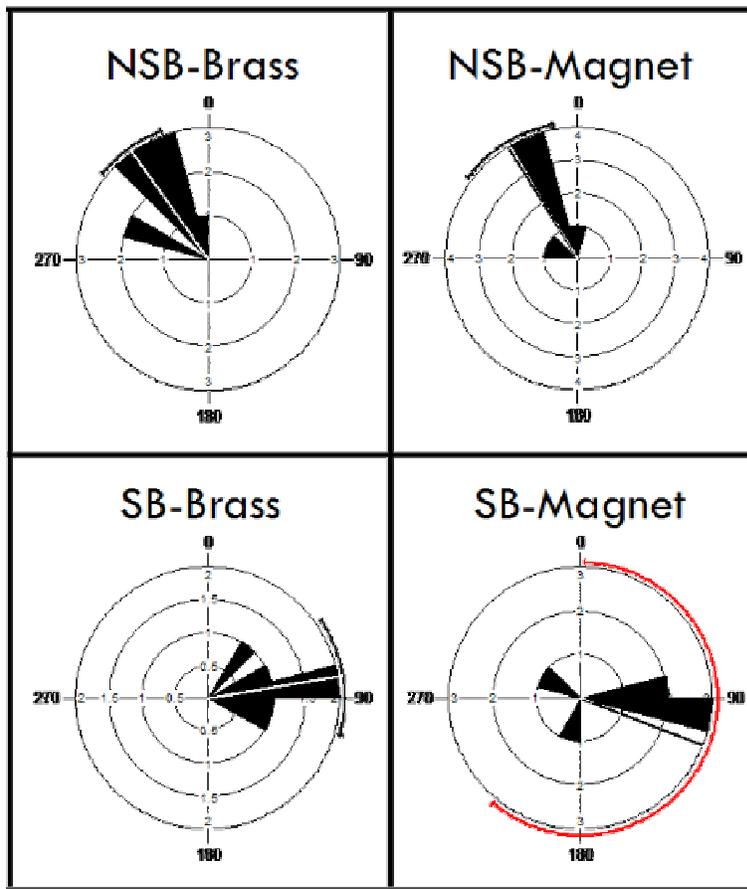


Figure 4

Distribution of directional estimates at Site 2.

Each mean vector was compared to the other mean vectors using a Watson-Williams F-test. Four significant differences were observed. The mean vector of Group NSB-B-2 differed significantly from both Groups SB-B-2 ($F = 85.63$, $p < .001$) and SB-M-2 ($F = 15.395$, $p = .001$). Likewise, the mean vector of Group NSB-M-2 differed significantly from both Groups SB-B-2 ($F = 54.547$, $p < .001$) and SB-M-2 ($F = 14.071$, $p = .002$). These differences suggest that blocking visual and auditory cues disrupts directional estimates, and this effect is independent of the presence of magnets.

The critical evidence that magnets influence directional estimates was not obtained. The presence of magnets did not influence directional estimates when visual and auditory cues were available ($F = 0.098$, $p = .758$) or when those cues were absent ($F = 0.702$, $p = .417$).

Like participants in no-sensory-block groups at Site 1, participants in no-sensory-block groups at Site 2 indicated that visual cues were the primary means by which directional estimates were made. However, there was no single visual cue used by all participants. Because Site 2 was a slightly recessed area with heavy vegetation growth, participants' view of the campus was limited. Rather than relying on a single visual cue, most participants indicated that their estimates were made with reference to multiple visual cues relative to the target location (i.e. cognitive mapping). Similar to findings from Site 1, most participants in sensory block conditions indicated that their estimates were guesses that were not based on any conscious experiences. Unlike findings from Site 1, the absence of visual and auditory cues was sufficient to produce significant changes in both sensory-block groups relative to the no-sensory-block groups. Thus, while the presence of magnets during sensory-block conditions was sufficient to influence responding at Site 1, no difference was observed between magnets and brass at Site 2. This difference in results between sites is difficult to reconcile. This is further complicated by the fact that the pattern of variability in sensory-block groups reverses between sites. Whereas the presence of brass buttons produce *greater* variability than magnets at Site 1, the presence of brass buttons produce *less* variability than magnets at Site 2.

III. EXPERIMENT 2

Murphy (1989) developed a laboratory analogue to Baker's (1980) experiment using a rotating chair. Participants were first placed in a rotating chair and shown the four cardinal directions (N, E, S, and W) which were written on the walls of the testing room. Participants were then ear-muffled, double-blindfolded, and brass bars (control group) or bar magnets (experimental group) were fixed to their temples. Participants were then slowly rotated clockwise and counterclockwise until the chair was stopped at a random position. When the chair was stopped, participants were asked to indicate which direction they were facing. Initial performance of all participants was excellent but performance rapidly deteriorated over the first several trials, suggesting that both groups initially attempted to follow the turns of the chair to make a decision. As the session progressed, many females switched to an alternate strategy, as indicated by improved performance in later trials, but most males did not. The finding that some humans can indicate the correct cardinal direction while other senses are blocked or suppressed has not been replicated, nor has the finding that females perform better than males (or vice-versa).

Method

Participants

Undergraduates and graduate students at Auburn University were recruited as participants. Forty participants were divided into four groups; 10 males wore magnets

(Group MM), 10 males wore brass buttons (Group MB), 10 females wore magnets (Group FM), and 10 females wore brass buttons (Group FB). All participants were free of any metallic surgical implants and removed all metal jewelry prior to testing.

Materials

A rotating reclining chair was used to rotate participants. Participants were required to wear modified welding goggles and earplugs identical to those used in Experiment 1. A sheet numbered from one to fifty was used by the experimenter to record participants' responses. The recording sheet also indicated the number of clockwise and counterclockwise turns to be made by the experimenter on each trial. A sheet of paper was placed on each wall containing the first letter of each cardinal direction (N, E, S, W) and a corresponding animal (newt, elephant, snake, wolf).

Procedure

Undergraduate and graduate students were recruited and divided into groups of males and females. Males and females were then randomly assigned to experimental (magnet) or control (brass) groups. Each participant, tested individually, was seated in a reclined rotating chair and shown a picture on each wall containing the first letter of the cardinal direction and a corresponding animal. After this, participants were instructed to insert earplugs and were blindfolded by the experimenter. Once affixed, participants were asked if they could detect any light through the goggles. If they indicated that light could be detected, the goggles were readjusted until no light was visible. Once the earplugs and goggles were appropriately attached to the participant, an elastic headband containing either six round magnets or six brass buttons was strapped to the participant's head at approximately mid-forehead level.

Participants were once again rotated to the four cardinal directions, and the experimenter verbally indicated what direction the participant was facing. The experimenter then informed participants that the experiment would begin. Participants were informed that they would be rotated clockwise and then counterclockwise. Once counterclockwise movement ceased, participants were free to make their directional estimate by *a)* stating the cardinal direction that they faced or *b)* saying the name of the animal associated with each cardinal direction. Before the first trial began, participants were instructed to refrain from counting turns as a means of estimating direction.

Each participant received 50 trials in which he/she was rotated clockwise and counterclockwise on each trial. Rotation on each trial was pseudo-randomly determined, and the total rotation on each trial (e.g. clockwise turns plus counterclockwise turns) did not exceed 720° (see Figure 5). All participants were tested using the same rotation schedule. The chair was rotated at a speed of approximately one turn per 10 seconds. Each trial was separated by an approximately 5 second inter-trial interval. The four cardinal directions were represented approximately equally in each trial. Participants received no feedback regarding their performance during or after testing.

| TRIAL | CLOCKWISE ROTATIONS | | COUNTERC ROTATIONS | |
|-------|---------------------|---|--------------------|---|
| 1 | 1 | N | 0.75 | E |
| 2 | 0.75 | N | 1 | N |
| 3 | 1 | N | 1 | N |
| 4 | 1 | N | 0.5 | S |
| 5 | 0.25 | W | 0.25 | S |
| 6 | 0.75 | E | 0.5 | W |
| 7 | 1.25 | N | 0.25 | W |
| 8 | 0.5 | E | 1.25 | N |
| 9 | 1 | N | 0.25 | W |
| 10 | 1.25 | N | 0.5 | S |
| 11 | 0.25 | W | 1 | W |
| 12 | 1.5 | E | 0.5 | W |
| 13 | 0.75 | S | 0.5 | N |
| 14 | 0.5 | S | 1 | S |
| 15 | 0.5 | N | 0.75 | E |
| 16 | 0.75 | N | 1 | N |
| 17 | 1 | N | 0.25 | W |
| 18 | 0.5 | E | 1.5 | W |
| 19 | 0.75 | S | 0.75 | W |
| 20 | 1.25 | N | 0.75 | E |
| 21 | 0.5 | W | 0.75 | N |
| 22 | 0.25 | E | 1 | E |
| 23 | 1 | E | 0.5 | W |
| 24 | 0.75 | S | 0.75 | W |

| | | | | |
|----|------|---|------|---|
| 25 | 0.5 | E | 1 | E |
| 26 | 0.75 | N | 0.5 | S |
| 27 | 0.5 | N | 0.75 | E |
| 28 | 1.5 | W | 0.25 | S |
| 29 | 0.25 | W | 0.75 | N |
| 30 | 0.25 | E | 1 | E |
| 31 | 1 | E | 0.25 | N |
| 32 | 1 | N | 0.5 | S |
| 33 | 0.5 | N | 1 | N |
| 34 | 0.25 | E | 0.25 | N |
| 35 | 1.25 | E | 0.75 | S |
| 36 | 1.5 | N | 0.25 | W |
| 37 | 0.5 | E | 0.75 | S |
| 38 | 0.75 | E | 1 | E |
| 39 | 0.75 | N | 0.5 | S |
| 40 | 0.75 | E | 1.25 | N |
| 41 | 0.25 | E | 1 | E |
| 42 | 0.25 | S | 1.25 | E |
| 43 | 0.5 | W | 0.25 | S |
| 44 | 0.75 | E | 0.5 | W |
| 45 | 0.75 | S | 0.75 | W |
| 46 | 1.75 | S | 0.25 | E |
| 47 | 1 | E | 0.75 | S |
| 48 | 0.75 | E | 1 | E |
| 49 | 0.75 | N | 0.5 | S |
| 50 | 1.25 | W | 0.75 | N |

Figure 5

Pseudo-random rotation schedule for indoors directional estimates experiment.

Once participants completed 50 trials, they were instructed to remove the headband, goggles, and earplugs and remain seated in the reclining chair. After

approximately 20 seconds, participants were given one hour of extra credit and were instructed to gather their belongings and leave.

The first 10 trials of each session were eliminated to reduce the effect of participants potentially using a turn-counting strategy early in the session. Mean number of correct responses on the last 40 trials was calculated for each group. Performance of groups was analyzed using a two-way ANOVA.

Results and Discussion

Mean number of correct responses per trial were compared using a two-way ANOVA (magnet presence x sex). There was neither a main effect of sex nor of presence of magnets, but a significant interaction was obtained (see Figure 6). Males ($n=20$, $M=13.4$, $S=5.082$) and females ($n=20$, $M=12.05$, $S=4.582$) produced an equal number of correct responses, $F(1, 36)=0.9038$, $p=.3481$. Likewise, participants in the magnet condition ($n=20$, $M=13.6$, $S=5.642$) and brass condition ($n=20$, $M=11.85$, $S=3.787$) produced an equal number of correct responses, $F(1, 36)=1.5188$, $p=.2258$. Although the effect of magnets was not significant, it is interesting to note that the three top performers in the experiment were in magnet-wearing groups (two males and one female).

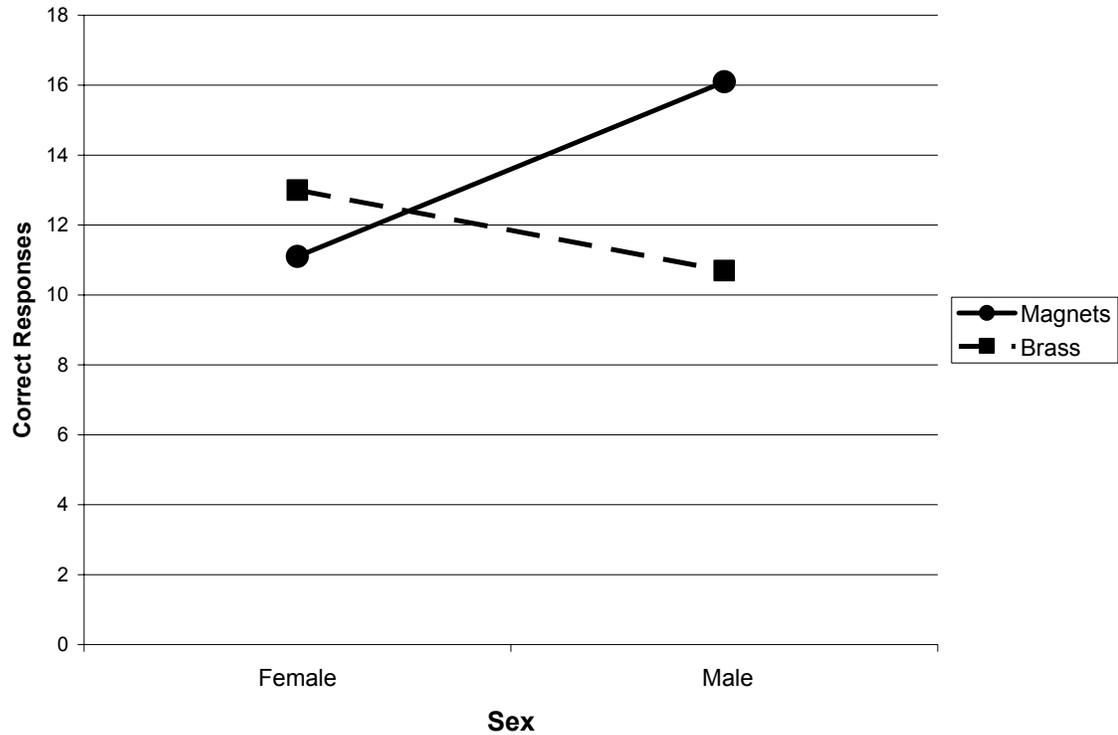


Figure 6

Mean correct responses for last 40 trials in indoors directional estimates experiment.

A significant interaction between the presence of magnets and sex was obtained, $F(39)=6.607$, $p=.0144$. Differences between groups were compared using two-way pairwise t-tests. Only one significant difference between groups was obtained. Males wearing round magnets ($n=10$, $M=16.1$, $S=5.043$) made significantly more correct responses than males wearing non-ferrous brass buttons ($n=10$, $M=10.7$, $S=3.592$), $t(9)=4.02$, $p=.003$.

Since Murphy (1989) noted that female performance did not improve until the latter part of sessions, we analyzed correct responses in the final 20 trials of each session. A two-way ANOVA was again used to compare correct responses. Similar to the analysis of the final 40 sessions, main effects for sex, $F(1, 36)=0.049$, $p=.8256$, and

presence of magnets, $F(1, 36)=0.444$, $p=.5097$, were not obtained. However, an interaction between sex and presence of magnets was again observed, $F(39)=8.982$, $p=.004$ (see Figure 7).

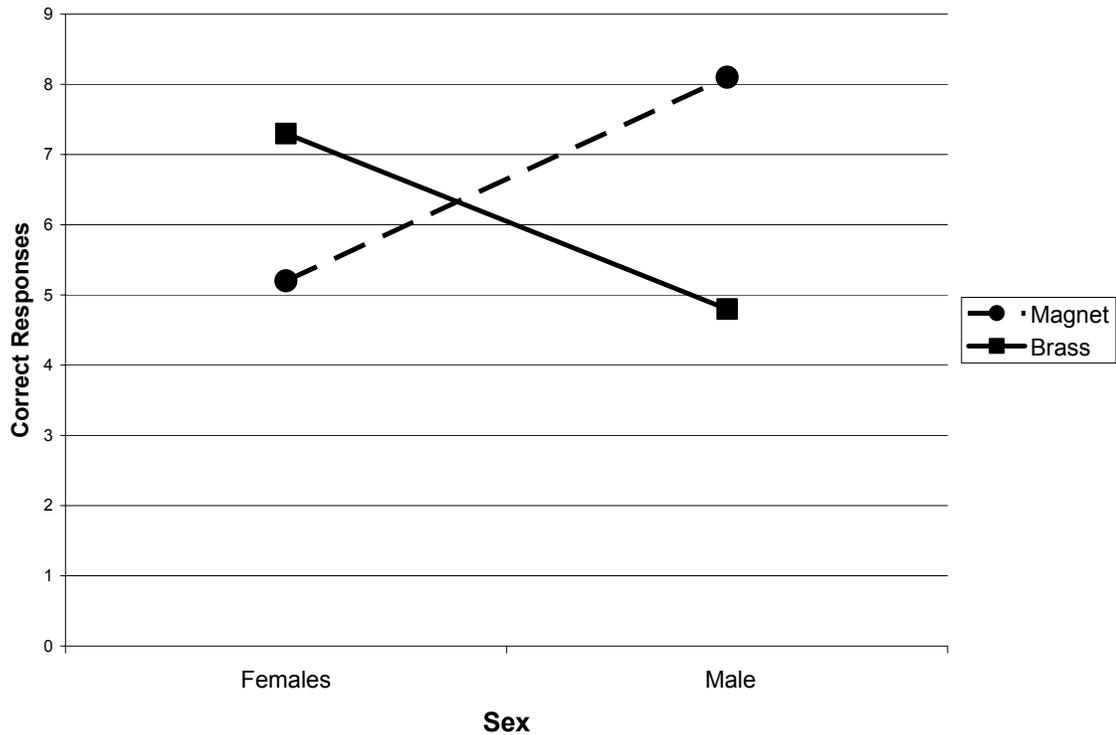


Figure 7

Mean correct responses for last 20 trials in indoors directional estimates experiment.

Using two-tailed pairwise t-tests, two significant differences between groups were observed. Similar to the analysis of the final 40 trials of each session, a significant difference was obtained between males wearing magnets ($n=10$, $M=8.1$, $S=2.961$) and males wearing brass ($n=10$, $M=4.8$, $S=2.781$), $t(9)=4.256$, $p=.002$. Unlike the earlier analysis, a marginally significant difference between males wearing magnets ($n=10$, $M=8.1$, $S=2.961$) and females wearing magnets ($n=10$, $M=5.2$, $S=2.781$) was obtained, $t(9)=2.225$, $p=.0531$.

Evidence that males wearing magnets outperform males wearing brass buttons has not previously been obtained. More importantly, the findings that males and females perform equally well and that magnets do not disrupt directional estimates in females is inconsistent with Murphy's (1989) findings that females perform significantly better than males and that the ability to make directional estimates is disrupted by the presence of magnets.

Whereas Murphy found that many females were able to accurately estimate their direction in the absence of auditory and visual cues, our results suggest that at a 99% confidence level, only males performed significantly above chance. The finding that males wearing magnets perform above chance is counterintuitive and is difficult to explain. The findings of this experiment are also difficult to reconcile with the mixed findings from our first experiment. Whereas, during Experiment 1, the presence of magnets disrupted directional estimates at Site 1, the present findings suggest an enhancement in directionality by the presence of magnets on the forehead. In the present experiment, the enhancement was only observed among males. Unfortunately, due to an unexpected discontinuation of Experiment 1, comparisons between sexes was not possible.

IV. EXPERIMENT 3

Both Bookman (1977) and Walker and Bitterman (1989) successfully trained a discrimination between the presence and absence of a magnetic field anomaly. However, this effect has never been observed in mammals. The purpose of the third experiment was to determine if a conditioned discrimination between the presence and absence of a magnetic field anomaly could be acquired among humans. To maximize the possibility of conditioning the discrimination, the magnetic field used for conditioning differed from that of Earth's field in intensity, polarity, and inclination.

Method

Participants

Four graduate students at Auburn University, two males and two females, were selected as participants. All participants were free of any metallic surgical implants and removed all metal jewelry prior to testing.

Apparatus

A specially designed chair and enclosure was built to hold the magnets and generate power to produce the magnetic fields. An electrical magnetic coil attached to each side of the apparatus produced a magnetic field around the head of the participant (see Figure 8). Magnets were placed approximately 12 inches apart, and the participant's head was placed between the magnets. The strength of the magnetic field, controlled by a DC power supply at 3.6 volts, was approximately 9.12 mT (milliTesla) at the surface of the magnetic coil and 0.67 mT at the center of the field. The strength of the magnetic field, controlled by a DC power supply at 0.3 volts, was approximately 1.35 mT at the

surface of the magnetic coil and 0.105 mT at the center of the field. The magnetic field was oval in shape and covered the entire head of the participant. The strength of the magnetic field was tested weekly using a gauss meter, and any changes in the field were corrected using the DC power supply. Two heavy-duty electrical switches were used to control the flow of current into the magnetic coils.



Figure 8

Front, rear, and side views of the custom-made chair and magnet enclosure used to deliver static magnetic fields.

A computer was used to deliver stimuli, for training functions, and to record all responses. A stereo was used to play a custom-made noise CD. The CD consisted of layers of white noise, pink noise, randomly-alternating pure tones, and recordings of sounds made by laboratory equipment. A custom-made soundproof box was used to house the electrical switches in order to reduce the sound made by the switches. Each participant wore disposable soft-foam earplugs that were designed to block up to 34dB.

Procedure

Each participant, tested individually, was seated in a chair in a specially designed enclosure that was built to hold the magnet and generate power for the magnetic fields. The experiment involved conditioning of a discrimination between the presence and absence of a static magnetic field that is stronger, of different polarity, and of different inclination than Earth's field.

Each trial began with a computer-generated "ping" sound and the magnetic field was simultaneously either turned on or remained off. The 9.1 mT (at 3.6 volts) or 1.35 mT (at 0.3 volts) surface reading of the magnetic field was oriented 90° counterclockwise of magnetic north. Participants were instructed to use the mouse to left-click on a small white block located on one of the computer monitors. Placement of the white block on the screen varied. Clicking on the white block caused it to disappear and reappear on the other computer monitor. This stimulus-response sequence continued for a total of four alternations per trial, inducing head movement through the magnetic field.

After these stimulus-response sequences, a small white box appeared in the center of both computer monitors. Participants were informed that each monitor (labeled either 'on' or 'off') was associated with the presence or absence of a magnetic field anomaly. They were instructed to try to determine the presence or absence of the field by clicking a white box on one of the monitors. When participants' responses were correct, the monitor turned green and flashed "correct". When participants' responses were incorrect, the monitor turned red and flashed "incorrect". Each trial lasted approximately ten seconds, followed by a 20 second intertrial interval (ITI). The duration of each trial was determined by observing the longest period of time required to locate four large objects on alternating screens and then choose one of two larger objects. A 20 second intertrial interval was selected because it allows the effect of the presented magnetic field to dissipate to earth-strength levels (as indicated by a compass). The artificial magnetic field dissipates in approximately three seconds, which left the participant in the presence of Earth's ambient magnetic field for approximately 17 sec. The schedule of magnetic field presentation was randomly determined by the computer program. The only limitation placed on the randomization was that no more than three of the same-type trials (magnet-on or magnet-off) could occur consecutively.

Subjects A.M. (female) and P.C. (male) were required to discriminate between the presence and absence of the artificial magnetic field when the DC power supply supplied 0.3 volts to the magnet. The resulting magnetic field was approximately 1.35 mT at the surface of the magnetic coil and 0.105 mT at the center of the magnetic field. Subjects J.B. (female) and R.Z. (male) were required to discriminate between the presence and absence of the artificial magnetic field when the DC power supply supplied 3.6 volts to

the magnet. The resulting magnetic field was approximately 9.1 mT at the surface of the magnetic coil and 0.67 mT at the center of the magnetic field. Because all subjects were required to move their heads during trials, the exact strength of the magnetic field to which they were exposed could not be determined.

Each participant received between 27 and 30 sessions, and each session contained 50 trials. Thus, each subject was exposed to approximately 1500 trials. Participants were compensated with four dollars per session. Each participant completed two or three control sessions. During control sessions, the wires connecting the electromagnet to the power supply were disconnected. Disconnecting the wires left all aspects of the experiment intact *except* the magnet did not produce a magnetic field. Sessions were separated by between one and twelve days. Most sessions were separated by no more than five days.

Because this experiment involved a within-subjects signal-detection design (e.g. all responses can be analyzed as hits, misses, false alarms, and correct rejections), data was analyzed by calculating d' for each session of each subject. The d' statistic is used to assess the sensitivity to a signal by comparing hits to false alarms. An increase in d' over the course of the thirty session indicates an increasing sensitivity to the presence of the magnetic field. While d' calculation normally allows for the determination of both sensitivity and bias, only sensitivity could be analyzed in this experiment. Analysis of bias via ROC curves requires presenting the signal (e.g. artificial magnetic field) at varying strengths, but due to limitations of our equipment adjusting signal strength within sessions was not possible.

Results and Discussion

Subject P.C.

Subject P.C. was a 26 year old male. P.C. was exposed to a magnetic field that was approximately 1.35 mT at the surface of the magnetic coil and 0.105 mT at the center of the field. Because Earth's ambient magnetic fields range from approximately 2.8 to 6 mT, the magnetic field used in this experiment was approximately half of Earth's field in its weakest form. The performance of P.C. was analyzed using a d' statistic, and his performance is diagramed in the figure below (see Figure 9).

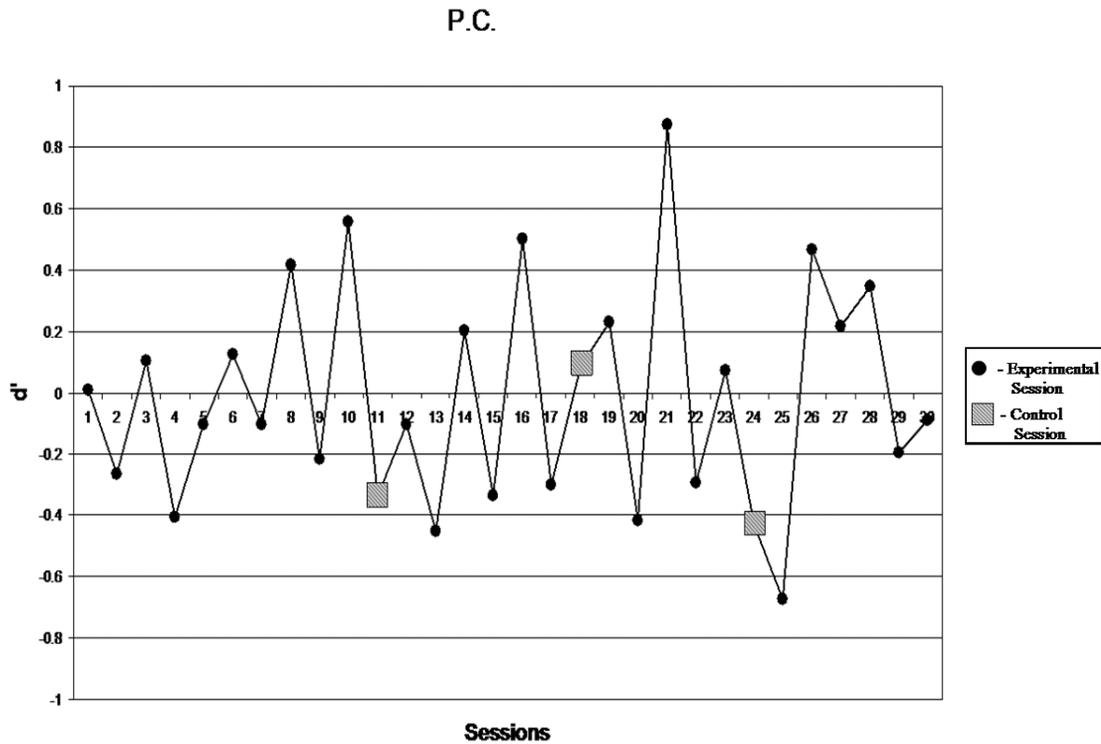


Figure 9

d' across sessions for P.C.

As expected, performance during the first several sessions appeared random. After the seventh session, variability in d' increased greatly and remained increased

throughout the entire experiment. Performance was best on the twenty-first session ($d' = 0.8748$) and worst on the twenty-fifth session ($d' = -0.6745$). Interestingly, the weak performance on the twenty-fifth session immediately followed a control session; thus, it is possible that P.C. changed response strategies due to its ineffectiveness during the control session. However, by the twenty-fifth session P.C. demonstrated a moderate sensitivity to the magnetic field that persisted for the next several trials.

Because of the high level of variability, it is difficult to determine whether P.C. was acquiring an ability to discriminate between the presence and absence of a magnetic field anomaly. However, an inspection of incorrect responses subtracted from correct responses indicates that positive variability (e.g. more correct responses) was generally higher than negative variability. Similarly, the mean of positive values of d' (0.3941) was higher than the mean of negative values of d' (-0.331) in the last ten sessions. This finding is amplified when the twenty-fifth session is removed; the mean of negative values of d' drops to -0.2478.

Since the number of trials per session and the total number of sessions were selected for practical reasons (i.e. limited resources, difficulty maintaining subject participation), it is possible that increasing the number of trials per session or increasing the total number of sessions would produce more easily-interpretable results. While variability increased across sessions and most variability was in a positive direction (e.g. more hits), the data obtained from P.C. is insufficient to determine if a magnetic discrimination was acquired.

Subject A.M.

Subject A.M. was a 25 year old female. A.M. was exposed to a magnetic field that was approximately 1.35 mT at the surface of the magnetic coil and 0.105 mT at the center of the field. Because Earth's ambient magnetic fields range from approximately 2.8 to 6 mT, the magnetic field used in this experiment was approximately half of Earth's field in its weakest form. The performance of A.M. was analyzed using a d' statistic, and her performance is diagramed in the figure below (see Figure 10).

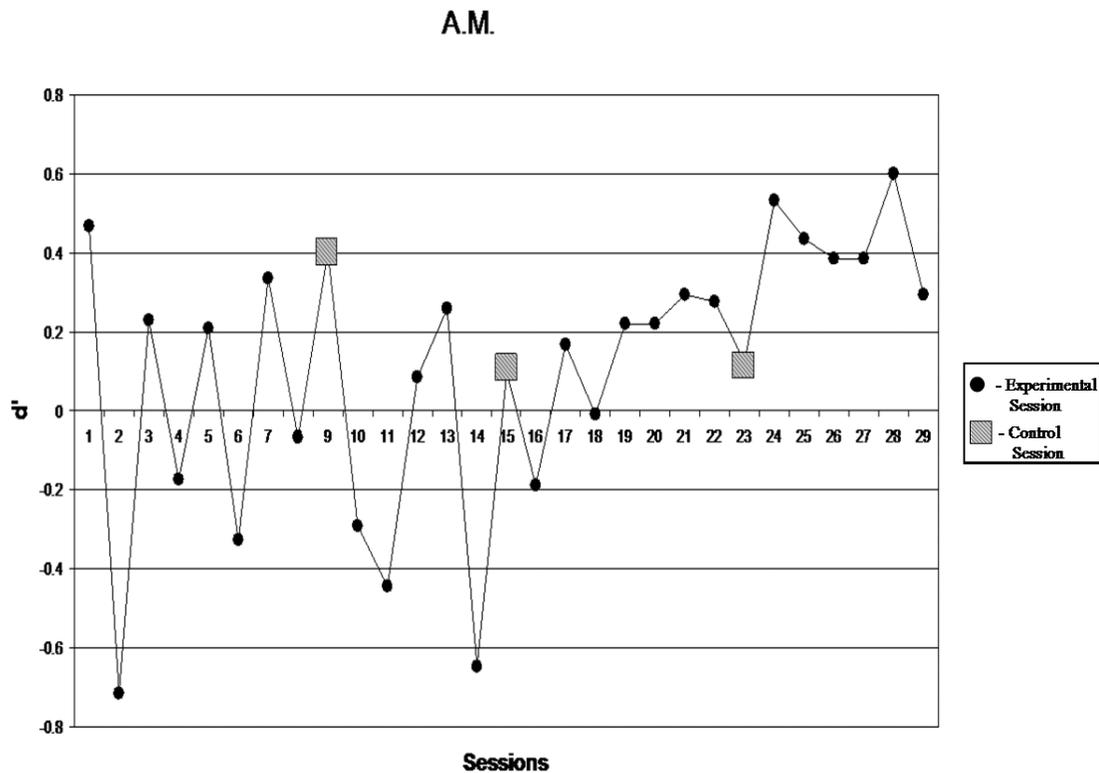


Figure 10

d' across sessions for A.M.

Similar to the performance of P.C., performance on early sessions appears random. Unlike P.C., variability in the first half of the sessions is much greater than in

the last half. Beginning with session eighteen, all values of d' were positive and an upward trend was observed for the remaining sessions suggesting greater sensitivity to the presence of the artificial magnetic field.

The average value of d' was notably higher in the last half of the sessions ($d' = 0.254$) than in the first half of the sessions ($d' = -0.0359$). The increase in d' across sessions is most evident in the final ten sessions in which the average d' was 0.3635. Interestingly, the control conditions during session 23 did not disrupt performance on subsequent sessions.

Unlike P.C., subject A.M. demonstrated an increase in sensitivity to the presence of the magnetic field across sessions.

Subject R.Z.

Subject R.Z. was a 25 year old male. R.Z. was exposed to a magnetic field that was approximately 9.12 mT at the surface of the magnetic coil and 0.67 mT at the center of the field. Because Earth's ambient magnetic fields range from approximately 2.8 to 6 mT, the magnetic field used in this experiment was approximately four times as strong as Earth's field at its weakest. While R.Z. was exposed to 30 sessions, only 28 sessions are presented below. Due to a technical error, one experimental session and one control session were ended prematurely and have been eliminated. The performance of R.Z. was analyzed using a d' statistic, and his performance is diagramed in the figure below (see Figure 11).

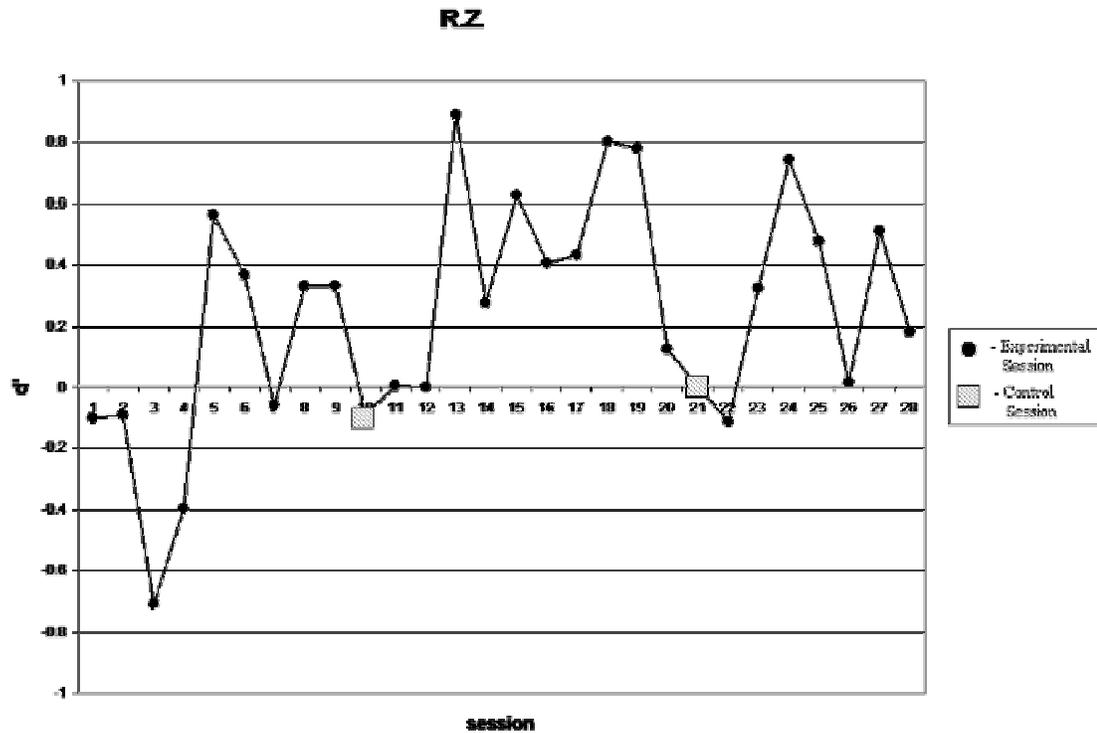


Figure 11

d' across sessions for R.Z.

Similar to the performance of A.M., early sessions were marked by high levels of variability and random performance between sessions. Beginning with session 13, R.Z.'s performance increased dramatically. He produced positive values of d' on every remaining session except the session that followed the control session (session 22).

Also similar to the performance of A.M., there was a notable increase in the average value of d' in the last half of sessions ($d' = 0.4078$) compared to the first half of sessions ($d' = 0.0938$). Performance on the final ten sessions ($d' = 0.3839$) was consistent with performance in the last half of the sessions.

R.Z.'s performance reflects acquisition of sensitivity to the anomalous electromagnetic field. Previous research by Murphy (1989) failed to demonstrate

disruption of directionality by placing magnets on the temples of male human subjects. However, it is important to note that the experiments of Murphy (1989) and Baker (1989) involved the disruption of *directionality* by static magnetic field. Whereas these experiments required both the detection of the presence or absence of a magnetic field anomaly *and* an ability to use Earth's ambient magnetic fields to determine one's cardinal direction, our experiment required only the detection of the presence or absence of a magnetic field anomaly

Subject J.B.

Subject J.B. was a 24 year old female. J.B. was exposed to a magnetic field that was approximately 9.12 mT at the surface of the magnetic coil and 0.67 mT at the center of the field. Because Earth's ambient magnetic fields range from approximately 2.8 to 6 mT, the magnetic field used in this experiment was approximately four times as strong as Earth's field at its weakest. Due to other obligations, J.B. was only able to complete 27 sessions. Since there would have been an intersession interval of nearly a month between the twenty-seventh session and the final three sessions, we decided to eliminate the final three sessions. The performance of J.B. was analyzed using a d' statistic, and her performance is diagramed in the figure below (see Figure 12).

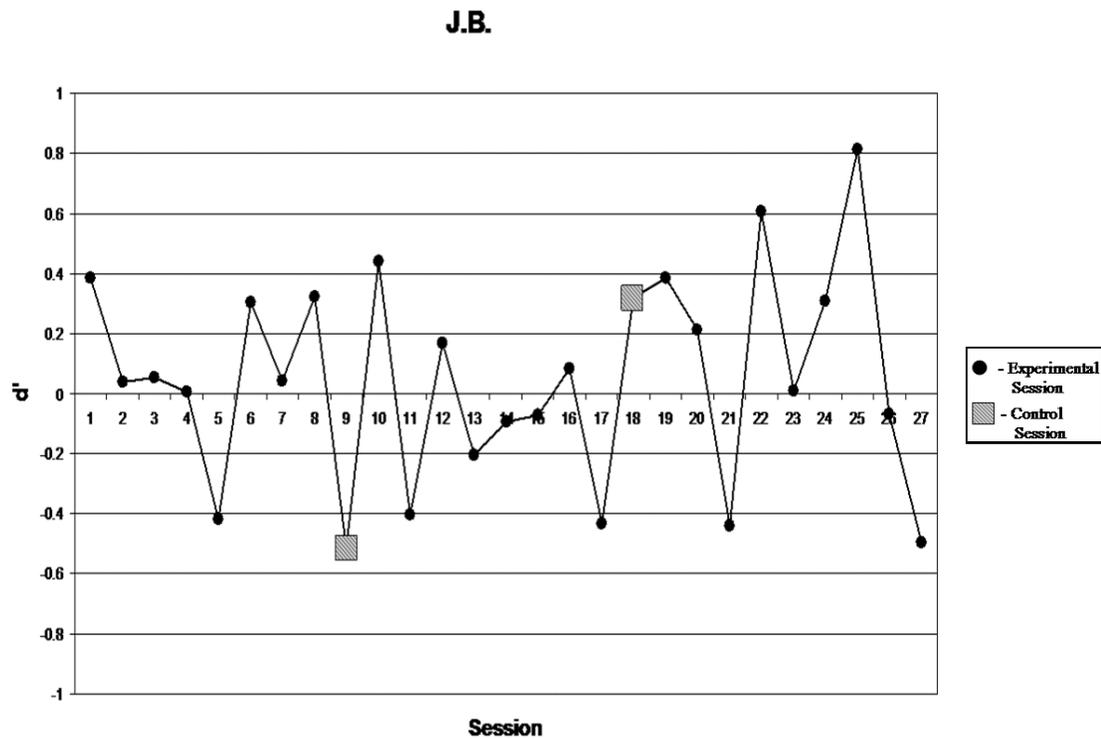


Figure 12

d' across sessions for J.B.

Subject J.B. produced a pattern of responding similar to that of P.C.: random responding throughout the experiment, but an increase in variability in later sessions. Performance was best on the twenty-fifth session ($d' = 0.8122$) and worst on the final session ($d' = -0.4946$). Mean performance in the last half of the sessions ($d' = 0.063$) was nearly identical to mean performance in the first half of the sessions ($d' = 0.032$). This finding was unchanged when analyzing only the final ten sessions ($d' = 0.09$). Thus, it appears that J.B. was unable to acquire an ability to discriminate between Earth's ambient fields and the electromagnetic field anomaly.

Similar to the performance of P.C., the increasing level of variability on later trials is difficult to interpret. Also similar to P.C., positive variability (e.g. more correct responses) was generally higher than negative variability. Unlike P.C., the mean of positive values of d' (0.3885) was virtually identical to the mean of negative values of d' (-0.3578) in the final ten session. Thus, while J.B. produced more positive values of d' than negative values in the final ten session, the roughly equal means of positive and negative values of d' in the final ten sessions suggests that J.B. was not acquiring an ability to discriminate between the presence and absence of the static magnetic field anomaly.

V. GENERAL DISCUSSION

Previous research on magnetoreception has demonstrated sensitivity to magnetic fields in a wide variety of species (e.g. Bookman, 1977; Beason, 1989; Kalmijn, 1982; Walker, 1984; Phillips, 1977). A more limited body of evidence has suggested that such sensitivity exists in mammals (Burda et al, 1990; Deutschlander et al, 2003; Baker, 1989). The present series of experiments was designed to investigate if and under what conditions magnetoreception occurs in humans.

Currently, there are two competing explanations regarding the mechanisms of magnetoreception. One theory regarding reception, the magnetite theory, suggests that deposits of a biologically-produced magnetic material (magnetite) are responsible for the magnetic sense (Kirschvink et al, 1985). Magnetite is distributed throughout the body, but among humans there is an abundance of magnetite in the meninges.

The other theory, the photopigment theory, suggests that shifts in magnetic fields result in variations in the triplet state of the photopigment rhodopsin through the process of optical pumping (Leask, 1977). Thus, the mechanisms of magnetoreception are linked to the visual system and can be influenced by light (Phillips and Borland, 1992).

Because both theories suggest that magnetic fields can influence behavior via physiological mechanisms located in the head, all of our experiments involved static magnetic field exposure to the head. Experiments 1 and 2 involved affixing a series of round magnets around the head. Because these magnets produce very localized fields

that are reduced dramatically as a function of distance, the round magnets exerted their affect within approximately one inch of the surface of the magnet. The electromagnetic fields used in Experiment 3 were much larger and thus penetrated the entire head. While the results of the experiments were mixed, some interesting and illuminating findings were made.

Experiment 1 was designed to determine if round magnets influenced humans' ability to judge direction. Because Baker (1980) found that humans can accurately judge the direction of a target location in the absence of visual cues and that the presence of magnets on the head disrupts this ability, we attempted to replicate his finding. The replication was expanded to investigate the ability to make estimates when all sensory cues are available and in the absence of both auditory and visual cues. Results of Experiment 1 contradict Baker's findings that humans can estimate the direction of a target in the absence of visual cues and that magnets disrupt this ability. We found that when auditory and visual cues were available, participants were able to accurately judge the direction of the target location but the presence of magnets did not affect this ability. Participants reported that they relied primarily on visual cues to make their estimate, but the strategy used differed at Sites 1 and 2. At Site 1, participants relied primarily on a set of tall stadium lights located next to the target location. At Site 2, which was slightly recessed and obscured a wide view of campus, participants made estimates based on the relationship between a variety of visual cues. The visual cues used at Site 2 varied between participants, but participants seemed to use familiar visual cues to create a cognitive map that allowed for accurate estimates.

In the absence of auditory and visual cues, participants' estimates were significantly different from the direction of the target location regardless of site of testing. At Site 1, the mean vector of participants wearing magnets differed significantly from both groups that had access to auditory and sensory cues. However, participants wearing brass buttons did not differ significantly from either of the groups that had access to auditory and visual cues. At Site 2, the estimates of participants in both magnet and brass groups were significantly different from those made by groups with access to auditory cues.

The critical evidence that magnets influence directional estimates was not obtained. When auditory and visual cues were available, the presence of magnets did not influence directional estimates. When auditory and visual cues were blocked, the presence of magnets did not affect estimates. Thus, round magnets placed on the head were insufficient to influence directional estimates. This finding is entirely inconsistent with Baker's (1980) finding.

The second experiment was a replication of Murphy's (1989) experiment in which she determined that females between the ages of 11 and 18 were able to accurately indicate their cardinal direction in the absence of visual cues and that the presence of round magnets on the head disrupted that ability. Whereas Murphy used an enormous sample of approximately 1300 participants, we selected a far more modest sample size. The use of a smaller sample size was both a pragmatic and a methodological decision. Because of our limited resources, such a large sample was not available. Also, the use of such a large sample decreases the criteria for significance and can produce data artifacts.

While Murphy found that magnets disrupted directionality, our findings suggest that magnets produced an enhancement in directional estimates in males. Males produced the highest number of correct responses, but the only significant difference we obtained was between males wearing magnets and males wearing brass. While there was a significant interaction between the presence of magnets and sex, an insignificant cross interaction can be observed in Figures 6 and 7.

Our results are nearly opposite of the findings of Murphy. Whereas she found that females could accurately estimate their cardinal direction and that the presence of magnets disrupted that ability, we found that only males wearing magnets could estimate their cardinal direction at a level above chance. It is difficult to determine why magnets would produce an enhancement in directional estimates, but the three participants who performed best were all wearing magnets.

Assuming that the magnetite-based magnetoreception theory is correct, the constant slow rotation of the chair in both directions may have prevented some magnetite particles from aligning north. If magnetite alignment is unstable and magnetoreception contributes to directional estimates, the instability of the magnetite may have resulted in inaccurate information being provided by the magnetoreception system. Conversely, when wearing magnets, all magnetite particles align with the magnets in the elastic headband and rotation does not cause realignment of magnetite particles. It is possible that the magnetoreceptive sense is only activated when magnetite particles move. In the absence of movement, magnetoreception may be disabled. Thus, the enhanced performance of males wearing magnets may reflect reliance on strategies that do not involve input from the magnetoreceptive sense. This is consistent with Bookman's

(1977) finding that movement is necessary for detection of magnetic field anomalies in pigeons. Our findings are inconsistent with the photopigment-based theory of magnetoreception. Assuming that magnets exert their influence through visual mechanisms, blocking visual cues should have disabled the magnetoreceptive system and produced equal performance between groups.

The final experiment in this series was designed to determine if discrimination between the presence and absence of a static electromagnetic field anomaly could be acquired. This experiment differed from our other experiments in some crucial ways. First, the experiment was not a replication. Whereas Baker (1980) mentioned conducting similar experiments unsuccessfully, he did not quantitatively report his findings. Second, electromagnetic fields were used to create the magnetic field anomaly. In the previous experiments, permanently magnetized material was used. The electrically-generated magnetic fields were larger and therefore penetrated more tissue. The use of electrically generated magnetic fields was necessary because it provided us with the ability to turn magnetic fields on and off. Because a DC power supply was used to produce the magnetic fields, the magnetic fields were similar to those produced by the round magnets in our earlier experiments. Finally, a small number of subjects were tested repeatedly over the course of two to three months. Thus, if magnetoreception is weak in humans due to disuse, the final experiment allowed participants to acquire the ability to detect magnetic fields over time.

Two magnetic field strengths were used. Two participants were exposed to weak fields (approximately 1/3 of Earth's strength at its weakest point and 27 times Earth's strength at its strongest point). This value was selected because it was the weakest field

that could be produced consistently by the DC power supply used to generate the field. The other two participants were exposed to much stronger fields (approximately 5 times Earth's strength at its weakest point and 180 times Earth's strength at its strongest point). Thus, at their strongest levels, the stronger fields were approximately seven times the strength of the weaker fields.

Two participants, P.C. and J.B., failed to acquire the ability to detect the presence of the magnetic field anomaly. However, their performance became increasingly variable as sessions progressed. This variability may reflect a change in strategies in later sessions. For instance, P.C.'s best performance occurred on the twenty-first session and his weakest performance occurred on the twenty-fifth session. P.C.'s weakest session occurred immediately following a control session. The control session may have resulted in a change in strategy that continued to be used ineffectively during the twenty-fifth session. On the twenty-sixth session, there was a rebound in performance ($d' = 0.4655$) which may reflect a return to the strategy that produced his best performance on the twenty-first session.

An analysis of variability in P.C.'s performance (see Figure 10) indicates that positive variability (e.g. correct responses) was markedly higher than negative variability (e.g. incorrect responses) throughout the experiment. Similarly, the average value of d' in the last half of sessions (0.0565) was higher than in the first half of the sessions (-0.0185). Whether this is indicative of slow acquisition is not clear, but the increase in variability suggests that an alternate strategy may have been adopted in later sessions.

The performance of J.B. was similar to that of P.C. in that an increase in variability was observed in later sessions. J.B.'s best performance occurred on the

twenty-fifth session ($d' = 0.8122$) and her worst performance occurred on her final session ($d' = -0.4946$). Unlike P.C., positive and negative variability were virtually identical both for the total number of sessions and for the final ten sessions. It appears that J.B. was unable to acquire the ability to detect the magnetic field anomaly, but the increase in variability in later sessions suggests that some change in response strategy may have been occurring. Because of resource limitations, we were not able to conduct more than 30 sessions per participant. Therefore, we cannot determine whether an effective strategy for discriminating between the presence and absence of a magnetic field anomaly was emerging.

The performance of A.M. and R.Z. is far more suggestive of magnetoreception. Both participants acquired a moderate ability to detect the magnetic field anomaly as evidenced by relatively consistent increases in d' across sessions (see Figures 11 and 12).

Early sessions by both participants produced random performance. Beginning with the thirteenth session, R.Z.'s performance began to stabilize, and he consistently produced positive values of d' throughout the rest of the experiment. The only exception to this was the twenty-second session which followed a control session. Like with P.C, the control session may have resulted in a change in strategy that continued to be used ineffectively during the twenty-second session. However, there was a rebound by the twenty-third session and values of d' remained positive for the remainder of the experiment. Average values of d' were markedly higher for the last half of sessions ($d' = 0.4708$) compared to the first half of sessions ($d' = 0.0938$). Thus, it appears that R.Z. acquired a moderate ability to detect the magnetic field anomaly.

A.M.'s performance reflects the strongest evidence of magnetoreception in humans. Early sessions are marked by high levels of variability and random performance. Beginning with the nineteenth session, A.M.'s performance began to stabilize and she produced positive values of d' for the remaining session. Unlike with other participants, the control session did not disrupt her performance on the following session.

It is unclear why two participants acquired an ability to detect the magnetic field while the other two did not. Acquisition does not appear to be related to field strength or sex; one female acquired the ability when exposed to weak fields and one male acquired the ability when exposed to strong fields. It is possible that the magnetoreceptive sense is activated by weaker magnetic fields in females and stronger magnetic fields in males, although this seems highly unlikely. Since the sense evolved in response to Earth's magnetic fields, it is difficult to explain why it would be tuned to supernormal stimuli.

Another possible explanation is consistent with Murphy's (1989) finding that females are sensitive to magnetic field anomalies. The weaker fields may have been within the range that human females are sensitive to, but this range may be outside of that of males. Since the stronger fields were roughly 200 times the strength of those produced by Earth, overloading the system may have produced a sensation that was perceived by males but not females. Again, it seems unlikely that males and females would be sensitive to different ranges of fields since both evolved in the presence of the same fields.

The explanation that is most logically consistent is that all participants were acquiring the ability to detect the presence of the magnetic field anomaly, but acquisition

proceeded at different rates across participants. A.M. and R.Z. produced patterns of responding that suggest acquisition, but the ability to reliably detect the field anomaly emerged at different times. R.Z. began an upward trend in d' on the thirteenth session, whereas A.M. began an upward trend on the nineteenth session. The decision to conduct 30 sessions per participant was selected for practical and semi-arbitrary reasons. Had we instead chosen to use 20 sessions, acquisition of detection would not have been observed in A.M.

Magnetoreception does not appear to be a primary sense in humans. This may be because of the reliability of other senses and/or because we spend a substantial amount of our lives in altered magnetic fields. If the sense is rarely used, it is likely that there would be great variability in the amount of time required gain control over it. Thus, the increased variability in later sessions by P.C. and J.B. may reflect a slower acquisition of detection or a sampling of strategies that could ultimately result in magnetic field detection. In the future, doubling the number of sessions per participant could clarify the meaning of P.C. and J.B.'s increased variability in later sessions. In any case, it is clear that the performance of P.C. and J.B. was not stable across sessions.

While we did not collect data on percepts experienced by participants, informal conversations with the participants reveal a common but unreliable sensation. At some points during the experiment, participants indicated that in the presence of the magnetic field anomaly they perceived a slight pull at the back of the throat and neck. When pressed further for details, participants were unable to expand on the nature of the sensation or pinpoint the locus of the sensation. It is important to note that this sensation was reported rarely, but it was reported at least once by each participant. Reports of the

sensation did not correlate with accuracy, and participants generally stated that the sensation did not last for the entire session. Participants reported that they unsuccessfully tried to use this sensation as the primary cue for making the discrimination. It is unclear whether this sensation is related to magnetoreception or if it is a psychosomatic byproduct of trying to master a difficult task. The observation that similar sensations were reported across participants suggests that the sensation was a product of the magnetic field anomaly. This sensation was never reported during control sessions.

Because we created magnetic field anomalies that differed from those of Earth in strength, polarity, and inclination, it is not possible to determine which dimension(s) of the fields influenced behavior. Since the best performance in Experiment 3, that of A.M., occurred with weaker fields, it is unlikely that field strength alone is responsible for magnetoreception. Similarly, fluctuations in field strength across the planet occur within a relatively narrow range and those fluctuations appear in an arbitrary fashion. Thus, variations in field strength are of very limited use for purposes of navigation.

Among birds, Beason (1989) provided evidence that magnetic fields are perceived via an inclination compass. Similar findings have been reported with red-spotted newts (Phillips, 1986a). Our manipulation created an inclination that was parallel to the surface of Earth. Functionally, the inclination was identical to that which exists at Earth's equator. If inclination was the primary cue attended to, testing humans at locations further from the equator should produce better performance since inclination increases as one moves away from the equator. No research has been conducted on the development of magnetoreception as a function of distance from the equator.

Although the results of our experiments are mixed, there is evidence that magnetic fields can influence human behavior. Relatively intense training over a substantial period of time appears to be required in order to detect the presence of magnetic field anomalies. While the results of Experiments 1 and 2 are contradictory in some ways, both suggest that magnets have a subtle influence on behavior. The mixed results in Experiments 1 and 2 may have occurred because magnets *were* influencing perception of direction, but the information could not be successfully integrated with other sensory input.

While detection of magnetic fields appears possible, it is unclear whether an ability to detect magnetic field anomalies can enhance navigational abilities. On most sessions in Experiment 3, participants did not report any unique sensation associated with the presence of the magnetic field anomaly and often indicated that their responses were blind guesses. Therefore, even if persons were able to perfectly master the task in Experiment 3, they may not be able to integrate that information with sensory systems to which we have conscious access. Future research should investigate whether extensive discrimination training with a magnetic field anomaly (similar to the task in Experiment 3) enhances performance on directional estimates tasks (similar to those used in Experiments 1 and 2).

Because humans spend a substantial period of time in altered magnetic fields and our navigation is often driven by deliberately arranged cues, it is likely that magnetoreception is suppressed in humans. Whereas non-human animals must rely on naturally-occurring environmental cues for navigation, humans in industrialized societies create cues that can be consciously processed by our best senses (i.e. road signs,

emergency alarms, etc.). Thus, the need for magnetic cues is reduced and/or made redundant by more readily available cues. If magnetoreception is weak in humans due to disuse, it should be stronger and more easily observed in non-industrialized areas. While it is difficult to examine participants in non-industrialized areas, the sense may be slightly amplified in persons who spend substantial periods of time in non-industrialized areas. Hikers, campers, and survivalists who often seek remote areas for recreational purposes may possess a more finely-tuned magnetoreceptive sense. Again, no research has investigated how amount of time spent in non-industrialized areas influences magnetoreception.

Although it has been empirically demonstrated in a wide variety of organisms, the magnetic sense generally receives the least attention in discussions of sensory systems. Perhaps this is due to its relatively recent discovery, or perhaps it is due to the difficulty in measuring magnetoreception in humans. While magnetic sense may or may not play an important role in human navigation, it plays a primary role in the navigation of other organisms including some mammals (e.g. Burda et al, 1990; Deutschlander et al., 2003; Mather & Baker, 1981).

Because magnetoreception has been identified in a large number of species ranging from insects to birds to mammals, it is logical to assume that magnetoreception was selected long before humans existed. It appears to be ubiquitous in the animal kingdom, and its absence in humans would be an exception. Because traits are generally selected out due their maladaptive nature or due to more advantageous adaptations, it is difficult to explain why the ability would *not* exist in humans. Reliance on other, more accurate senses would not likely result in magnetoreception being selected out since

many senses provide redundant information about the environment. It is difficult to imagine how magnetoreception could be maladaptive in humans since it has been selected in such a wide variety of other species.

Assuming that magnetoreception occurs via magnetite, the presence of a large number of magnetite particles distributed throughout the body is suggestive of magnetoreception in humans. Since magnetite must be biologically manufactured (rather than acquired through diet) and appears to serve no function other than aligning with magnetic fields, magnetite is the likely cause of magnetoreception. Presently, the mechanisms by which magnetite may provide sensory input are unknown.

The finding that sensory systems often provide redundant information about direction has major implications for the manner in which behavioral experiments regarding movement are conducted. Deutschlander et al. (2001) demonstrated that the angle at which hamsters were housed directly influenced the location of their nesting in an experimental apparatus, purportedly due to the hamsters' magnetic sense. Consider an experiment on the effects of olfactory cues on hamster nesting in which both groups were housed in the same room but Group 1 was placed against the east wall and Group 2 was placed against the north wall. During testing, hamsters would be placed in identical testing apparatuses that differ only in subtle odor cues. When differences between the two groups' nesting behavior are observed, the experimenter is likely to attribute the differences to odor cues when such an interpretation may not be warranted. While most researchers are likely to control for visual, auditory, and olfactory cues, few control for magnetic cues.

Redundancy in sensory information has implications for the study of all sensory systems. One may observe that a rat is able to quickly maneuver through a complex maze. Hypothesizing that the rat accomplishes the task by the use of visual cues, the experimenter may block all sensory systems except vision. If the rat quickly maneuvers through the maze, the experimenter may conclude that vision is the primary means by which navigation is accomplished. This conclusion may or may not be correct. Vision may be *sufficient* but not *necessary* for navigation; in fact, when no senses are blocked, the rat may primarily use subtle olfactory cues or a combination of cues for navigation. Conversely, the experimenter may block all sensory systems except vision and find that the rat is unable to navigate through the maze. He may then conclude that vision is not involved in rat navigation. Again, this may or may not be correct. Blocking all other sensory systems may cause a general confusion or disorientation that interferes with the rat's ability to attend to visual cues or the visual system may require input from other sensory systems to be effective. In this case, one cannot make conclusions about sufficiency or necessity.

A major problem facing researchers is how to isolate sensory systems. While simple on its face, the issue is incredibly complex. The experimenter has one of two options: block the stimuli that activate the sensory systems or deactivate the sensory system itself. The former has practical limitations; it may be difficult, if not impossible, to remove *all* cues related to any sense due to variations in the sensitivity of sensory systems of different organisms. While the researcher may not notice any auditory cues in his or her lab, an organism with a more keen sense of hearing may. Certainly, special precautions must be taken (i.e., the use of specialized equipment to detect specific cues)

to ensure that no cues are present. Controlling for magnetic cues is far more difficult; reducing magnetic cues to zero G would require iron shielding of housing chambers, testing apparatus, and the path between the two, and any electrical equipment located within any of these areas may influence one's results. When one moves experimentation to a natural environment, the idea of blocking stimuli that activate sensory systems must be abandoned in favor of deactivation of the sensory system itself. Deactivation of some sensory systems is fairly simple. For example, zinc sulphate destroys the olfactory mucosa, effectively eliminating olfaction in pigeons (Bingman & Benvenuti, 1996). Other sensory systems are too poorly understood to allow for adequate deactivation. For instance, covering the eyes of the salamander would seem sufficient to block visual cues, but extraocular organs located somewhere on the head are responsible for *polarized* light detection which plays a crucial role in salamander navigation (Adler & Taylor, 1973). Deactivation of the magnetoreception system is currently impossible because we do not know the location of the receptors or the means by which magnetic fields exert their effects.

Attempting to separate the integrated sensory system of animals into discrete subsystems is problematic in itself since they coevolved. Thus, isolating and studying any particular sense may distort the actual operation of that sense. This is most apparent in behavioral research on movement: if only a single sense is activated and the expected movement is observed, the researcher may be tempted to suggest that the sense is a necessary component of navigation. However, deactivation of some senses may result in an enhancement of others. Consider the cues used by migratory birds; the sun, moon, stars, magnetic fields, visual landmarks, and atmospheric odors (at least) influence

movement. If a bird relies primarily on solar cues to reach a destination during the day, dusk (at which time neither the sun nor moon is plainly apparent) may make magnetic or olfactory cues more salient. Since the senses coevolved, it seems likely that senses that provide redundant information may influence each other.

Finally, it is important to note that, by many standards, magnetoreception may not be considered a true sense. Of the five accepted senses (vision, olfaction, audition, gustation, and tactile senses), the physical stimulus, receptors involved in transduction, neural pathways, and brain areas involved in processing the stimulus are relatively well understood. With magnetoreception, only the physical stimulus is known. Additionally, human subjects can report how the stimulus is perceived with all senses except magnetoreception. If all of these criteria must be met, magnetoreception is not a sense. However, all of the criteria should not be weighted equally; knowledge of a physical stimulus that affects behavior is the primary criterion by which senses should be evaluated. Converging evidence that manipulation of a magnetic field influences a wide variety of biological functions, not the least of which is navigation, suggests that the way we qualify sensory systems should be reevaluated. At present, it seems appropriate to label magnetoreception a sensory system.

REFERENCES

- Able, K. A., & Gergits, W. F. (1985). Human navigation: Attempts to replicate Baker's displacement experiment. In J. L. Kirschvink, D. S. Jones, & B. J. MacFadden (Eds.), *Magnetite Biomineralization and Magnetoreception In Organisms* (pp. 569-572). New York: Plenum Press.
- Alsop, B. (1987). A failure to obtain magnetic discrimination in the pigeon. *Animal Learning & Behavior*. 15(2), 110-114.
- Baker, R. R. (1980). Goal orientation by blindfolded humans after long-distance displacement: Possible involvement of a magnetic sense. *Science*. 210, 555-557.
- Baker, R. R. (1981). *Human Navigation and the Sixth Sense*. New York: Simon and Schuster.
- Baker, R. R. (1989a). Navigation and magnetoreception by horses and other non-human land mammals. *Proceedings from the 1989 Conference of the Royal Institute of Navigation: Orientation and navigation – birds, humans, and other animals*. London: Royal Institute of Navigation.
- Baker, R. R. (1989b). *Human navigation and magnetoreception*. Manchester: Manchester University Press.
- Beason, R. C. (1989). Magnetic sensitivity and orientation in the bobolink. *Proceedings from the 1989 Conference of the Royal Institute of Navigation: Orientation and*

navigation – birds, humans, and other animals. London: Royal Institute of Navigation.

- Beason, R. C., Wiltschko, R., & Wiltschko, W. (1997). Pigeon homing: Effects of magnetic pulses on initial orientation. *The Auk*. 114(3), 405-415.
- Bookman, M. A. (1977). Sensitivity of the homing pigeon to an Earth-strength magnetic field. *Nature*. 267, 340-342.
- Burda, H., Marhold, S., Kreilos, I., Wiltschko, R., & Wiltschko, W. (1990). Magnetic compass orientation in the subterranean rodent *Cryptomys hottentotus*. *Experientia*. 46, 528-530.
- Delius, J. D., & Emmerton, J. (1978). Sensory mechanisms related to homing in pigeons. In K. Schmidt-Koenig & W. T. Keeton (Eds.), *Animal Migration, Navigation, and Homing* (pp. 35-41). Berlin: Springer-Verlag.
- Deutschlander, M. E., Freake, M. J., Borland, C., Phillips, J. B., Madden, R. C., Anderson, L. E., & Wilson, B. W. (2003). Learned magnetic compass orientation by the Siberian hamster, *Phodopus sungorus*. *Animal Behaviour*. 65, 779-786.
- Goff, M., Salmon, M., & Lohmann, K. J. (1998). Hatchling sea turtles use surface waves to establish a magnetic compass direction. *Animal Behaviour*. 55(1), 69-77.
- Hornung, U. (1993). Perception of earth strength magnetic fields in pigeons (*Columbia livia*). *Proceedings from the 1993 Conference of the Royal Institute of Navigation: Orientation and navigation – birds, humans, and other animals*. London: Royal Institute of Navigation.
- Kalmijn, A. J. (1982). Electric and magnetic field detection in elasmobranch fishes. *Science*. 218(4575), 916-918.

- Kiepenheuer, J., Ranvaud, R., & Maret, G. (1986). The effect of ultrahigh magnetic fields on the initial orientation of homing pigeons. In G. Maret, N. Broccara, & J. Kiepenheuer (Eds.), *Biophysical Effects of Steady Magnetic Fields (189-193)*. Heidelberg: Springer-Verlag.
- Kimchi, T., & Terkel, J. (2001). Magnetic compass orientation in the blind mole rat *Spalax ehrenbergi*. *Journal of Experimental Biology*. 204, 751-758.
- Kirschvink, J. L., Jones, D. S., & MacFadden, B. J. (Eds.) (1985). *Magnetite: Biomineralization and Magnetoreception In Organisms*. New York: Plenum Press.
- Kirschvink, J. L., Padmanabha, S., Boyce, C. K., & Oglesby, J. (1997). Measurement of the threshold sensitivity of honeybees to weak, extremely low-frequency magnetic fields. *The Journal of Experimental Biology*. 200, 1363-1368.
- Mather, J. G., & Baker, R. R. (1981). Magnetic sense of direction in woodmice for route-based navigation. *Nature*. 291, 152-155.
- Murphy, R. G. (1989). The development of magnetic compass orientation in children. *Proceedings from the 1989 Conference of the Royal Institute of Navigation: Orientation and navigation – birds, humans, and other animals*. London: Royal Institute of Navigation.
- Phillips, J. B. (1977). Use of the earth's magnetic field by orienting cave salamanders. *Journal of Comparative Physiology*. 121, 273-288.
- Phillips, J. B. (1986a). Magnetic compass orientation in the eastern red-spotted newt (*Notophthalmus viridescens*). *Journal of Comparative Physiology*. 121, 273-288.

- Phillips, J. B. (1986b). Two magnetoreception pathways in a migratory salamander. *Science*. 233(3), 765-767.
- Phillips, J. B., & Adler, K. (1978). Directional and discriminatory responses of salamanders to weak magnetic fields. In K. Schmidt-Koenig & W. T. Keeton (Eds.) *Animal Migration, Navigation, and Homing* (pp. 325-333). Berlin: Springer-Verlag.
- Quentmeier, B. (1989). Cardiac and respiratory responses to magnetic fields in pigeons. *Proceedings from the 1989 Conference of the Royal Institute of Navigation: Orientation and navigation – birds, humans, and other animals*. London: Royal Institute of Navigation.
- Quinn, T. P. (1980). Evidence for celestial and magnetic compass orientation in lake-migrating sockeye salmon, *Oncorhynchus nerka*. *Journal of Comparative Physiology A: Sensory, Neural, & Behavioral Physiology*. 137(3), 243-248.
- Viehmann, W. (1979). The magnetic compass of blackcaps (*Sylvia atricapilla*). *Behaviour*. 68(1-sup-2), 24-30.
- Walcott, C., Gould, J. L., & Lednor, A. (1988). Homing of magnetized and demagnetized pigeons. *Journal of Experimental Biology*. 134, 27-41.
- Walker, M. M. (1984). Learned magnetic field discrimination in yellowfin tuna, *Thunnus albacares*. *Journal of Comparative Physiology*. 155, 673-679.
- Walker, M. M., & Bitterman, M. E. (1985). Conditioned responding to magnetic fields by honeybees. *Journal of Comparative Physiology*. 157, 67-73.

- Walker, M. M., & Bitterman, M. E. (1989a). Honeybees can be trained to respond to very small changes in geomagnetic field intensity. *Journal of Experimental Biology*. 145, 489-494.
- Walker, M. M., & Bitterman, M. E. (1989b). Attached magnets impair magnetic field discrimination by honeybees. *Journal of Experimental Biology*. 141, 447-451.
- Wiltschko, W., & Wiltschko, R. (1972). Magnetic compass of European robins. *Nature*. 176(4030), 62-64.