DIFFERENTIAL LEARNING AND USE OF GEOMETRIC

ANGLES BY PIGEONS AND HUMANS

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ABSTRACT

The use of environmental geometry as a spatial cue is well established for a range of species. The theory of the geometric module posits that environmental geometric properties are processed within a dedicated neural module separate from that of featural processing. Since previous research has focused largely on the use of *global geometry* (e.g., the shape of a room) comparatively less is known about how *local geometry* (e.g., corner angles within a room) is encoded. The purpose of the research presented in this thesis was to examine how angular information is encoded and to determine whether angle size influences encoding. Chapter 2 presents a study during which pigeons were trained to discriminate between a small (60°) and large (120°) angle. Once the birds learned the task they were tested on their ability to discriminate between their training angle and one of a series of novel angles. The pigeons showed an absolute learning pattern for the small training angle, but not the large angle. The significance of this result is that the small angle may have been perceived as more distinctive compared to the large angle. Adopting a comparative approach, Chapter 3 presents a study during which adult humans were trained and tested using a similar paradigm but with different training angles (25°, 50° and 75°). The results of this study also support an absolute learning pattern for the small training angle but not the large. These results are significant in that they suggest that angle size may be an important local geometric cue that is encoded in a similar way by both pigeons and humans. To understand how angular information may be processed during a spatial task, Chapter 4 presents a study during which adult humans were trained and tested on their ability to use local angles (either 50° or 75°) to find a goal location within an object array. The results showed that the smaller angle was used more effectively as a spatial cue than the larger angle. Overall, these results are important as they suggest that small angles are perceived

by both pigeons and humans as more distinctive and thus more featural-like than large angles,

results that directly conflict with the modular theory of geometric encoding.

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CHAPTER ONE

General Introduction

For any mobile animal to survive it must be able to successfully navigate its environment. Whether traveling to find food, search for a mate, or simply to find its way home, it is essential that an animal have a workable spatial knowledge of its surroundings. How an animal journeys to a specific location and back again – whether it is a bee traveling hundreds of meters (Cartwright & Collett, 1983; Collett & Collett, 2002; Dacke & Srinivasan, 2007) or a pigeon traveling hundreds of kilometres (Loale, Wallraff, Papi, & Foa, 1983) – some of the same basic challenges posed by spatial navigation exist, even though they may not always be addressed or attended to in exactly the same manner by all species. In terms of visually-based spatial cues, generally speaking there are two types of cues that an animal has at its disposal when trying to determine its environmental position: *featural cues* and *geometric cues*. Featural cues include aspects such as the color of a building or the unique shape of a tree whereas geometric cues represent perceptual measurements such as direction and distance between objects or surfaces. Within an indoor space a featural cue might consist of the color of a given wall whereas a geometric cue would consist of the length of that wall. Although it is possible that a featural cue alone (e.g., a distinct object) can be used to mark a specific position in space – a concept known as *beaconing* – real life rarely affords this luxury and as a consequence the success or failure of a navigational venture often hinges on an animal's knowledge of the underlying relationship between features and geometry of the items contained within its environment. Whereas the manner in which environmental features are learned is easily apparent and has received considerable attention, less is known about how environmental geometry is learned. How does an organism learn about the geometric relationships between items within its environment?

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Specifically, what are the behavioural mechanisms involved in geometric learning? This thesis will attempt to answer this question by focusing on the nature of the learning of one specific type of geometric cue, that being the geometric properties of angles, the kind that would normally be found at the corner between two walls of a room for example. By using two different kinds of paradigms, one being a visual discrimination task and the other being a reorientation task, as well as two different species of subjects (pigeons and adult humans), a clearer understanding of how geometric angles, and in a broader sense geometric cues in general, are processed and learned will be elucidated.

The process of spatial navigation is one built on decision-making, and it is how and why these decisions are made that can make its study surprisingly complex. Consider for example a homing pigeon (*Columbia livia*) that has been displaced many miles from its home loft before setting out on a return journey back. It may begin the trip initially relying upon a directional cue such as the sun compass (Budzynski, Gagliardo, Loale, & Bingman, 2002; Wiltschko, Haugh, Walker, & Wiltschko, 1998; Wiltschko & Wiltschko, 1981), or perhaps by using its own magnetic compass that is sensitive to the Earth's magnetic field (Dennis, Rayner, & Walker, 2007; Walker, Dennis, & Kirschvink, 2002; Wiltschko & Wiltschko, 1978; Wiltschko & Wiltschko, 1996), or even possibly using olfactory cues carried along by the wind (Loale, Nozzolini, & Papi, 1990; Wallraff, 2004; Wallraff & Neumann, 1989). At some point along the journey it may alter its course in response to a particularly salient landmark such as a mountain range or a body of water (Biro, Freeman, Meade, Roberts, & Guilford, 2007) or even as recently been shown, highways (Lipp et al., 2004). As it gets closer to home it may further shift its focus to familiar landmarks positioned near its home loft as its primary source of information (Holland, 2003).

How these various types of navigational cues are incorporated into a mental map for future use has been the subject of different theories, the most notable being Cognitive Map Theory (O'Keefe & Nadel, 1978). This theory posits the learning of an allocentric (viewpoint-independent) spatial relationship between features and geometry that allows an organism to accurately navigate a previously learned environment. The neurological structure that critically mediates this process is the hippocampus and lesions to this area can profoundly impair spatial learning in both mammals (Pearce, Roberts, & Good, 1998) and birds (Vargas, Petruso, & Bingman, 2004). Importantly, Cognitive Map Theory suggests that a spatial environment can be learned sufficiently from a single viewpoint, with both the addition of new landmarks and the elimination of familiar ones processed quickly and efficiently such that a revised form of the cognitive map is updated accordingly. Subsequent theories building upon the basic premise of the Cognitive Map Theory have suggested a greater need for multiple egocentric viewpoints during learning, particularly within larger and more complex environments where important spatial divisions may exist (Poucet, 1993). Still other theorists have placed a premium on egocentric viewpoint-dependent learning in general as being the essential component during initial navigation of new environments (Wang & Spelke, 2002). A balance between these differing theories suggests complementary and interchanging roles for both egocentric and allocentric learning, with egocentric encoding being processed in parietal regions and allocentric coordinates processed within the hippocampal formation (Burgess, 2006).

In terms of the differential encoding of environmental properties research suggests that global geometric boundaries are processed implicitly whereas featural landmarks are processed explicitly through trial by trial associative learning (Doeller & Burgess, 2008). As shown by Biegler and Morris (1993) this dichotomy in learning features and geometry can be attributed to

the fact that landmarks must first be established as stable and reliable markers within an environment before they can be used effectively, an obligation that more permanent geometric boundaries necessarily already meet. Subsequent research has indeed shown that associative learning principles such as overshadowing and blocking apply to featural landmark learning within the spatial domain. For example, landmarks that are closer to a goal location can impair learning of those landmarks further away, findings that have been shown in pigeons in both touch-screen environments (Spetch, 1995) as well as real-world laboratory-based spatial environments (Cheng, 1988).

The fact that navigation is a dynamic process involving moment-to-moment decision makes it difficult to track accurately. Therefore, in order to fully understand the spatially-based decisions that are being made at any given time, a degree of parsimony is needed. It was through the development of the reorientation paradigm that the learning and use of different spatial cues could be studied within a static environment and the availability of these cues could be tightly controlled.

Cheng (1986) introduced the reorientation paradigm in his pioneering study that focused on the use of features and geometry by rats in a rectangular-shaped space. The rats were trained to find a food reward concealed at one corner of a rectangular-shaped enclosure whereby each corner was marked by a distinctively patterned panel in addition to a distinctive scent (e.g., vanilla). In addition to these featural cues, the rectangular shape of the enclosure provided geometric cues in that the reinforced corner was always situated along one short wall that was consistently flanked either to the right or left by a long wall (see *Figure 1-1*). Importantly, the corner diagonally opposite to the rewarded corner contained these exact same geometric properties, thus making the two corners identical according to geometric information alone.

Before each trial, the rat was disoriented by being placed inside a light-tight box that was slowly rotated on its axis, thus eliminating the rat's ability to use inertial cues. What makes the Cheng study noteworthy is the curious search behaviour displayed by the rats during a working memory version of the task. In this instance the rats were trained to find the reward located at one of the corners during a single training trial, and then following this trial they were placed inside an identical version of the training enclosure with one exception – the featural cues (i.e., the panels and scents) were rotated one corner clockwise – thus putting them in conflict with the correct geometric cues from training (see *Figure 1-2*). Surprisingly, in the test enclosure, the rats preferred to search at either of the two geometrically correct corners learned from initial training instead of following the more seemingly salient features to their new positions. They did this despite the fact that during training the geometry alone was only 50% predictive of the reward location whereas the features were 100% predictive. During a reference memory version of the same task the rats could eventually learn to use the features to localize the rewarded corner although this took a high number of training trials for them to accomplish. Overall, the results from Cheng (1986) spoke to the strong influence that the geometric properties of a spatial environment could have on rats when trying to determine their position following disorientation.
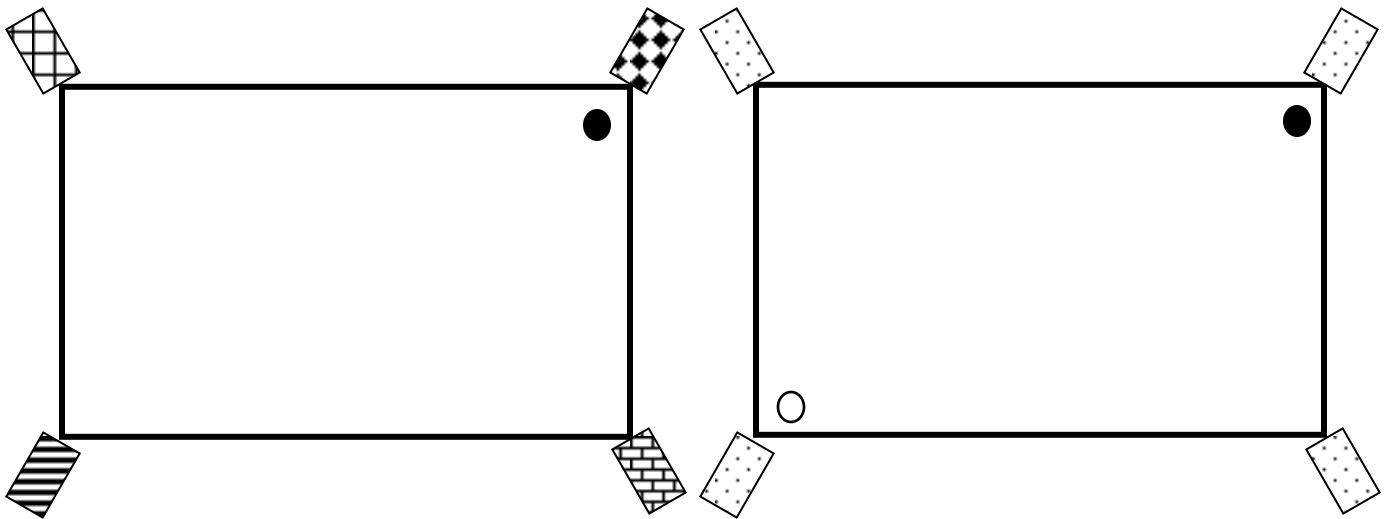
Figure 1-1 A schematic representation of the rectangular enclosure used by Cheng (1986). Left: A distinctive panel was located on the wall at each corner. During training trials individual rats learned to find food hidden at one correct corner (indicated by the black circle). Right: During testing the featural cues are no longer informative leaving the geometry of the environment as the only useable cue. The correct corner is once again indicated by the black circle whereas the corner diagonally opposite this corner contains the same geometric properties (indicated by the open circle).
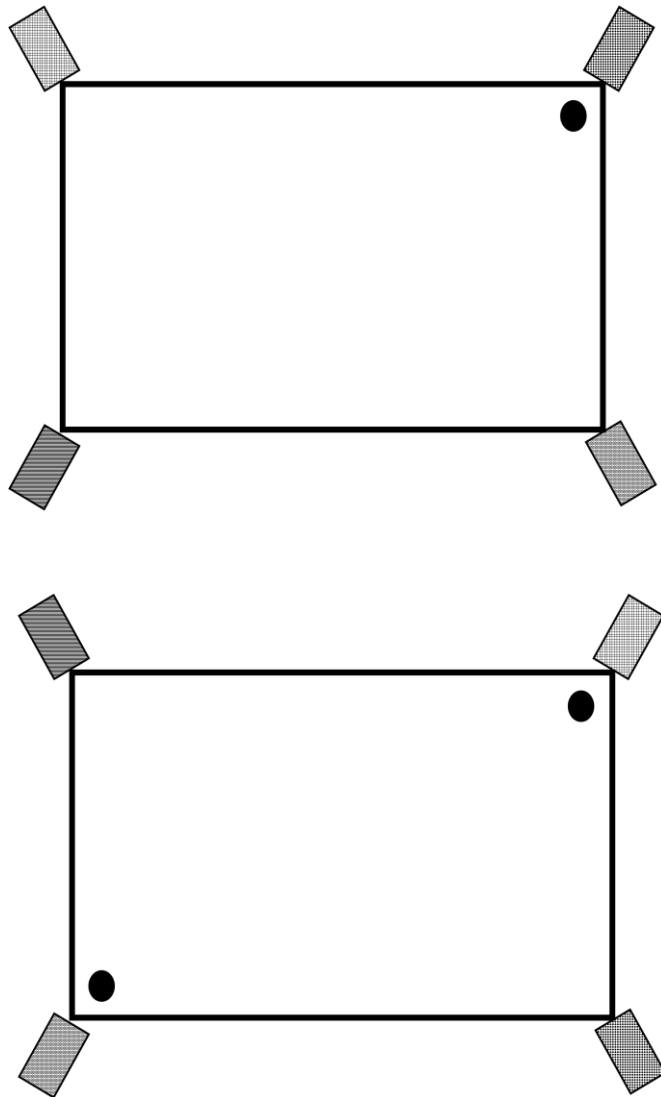
Figure 1-2 A schematic representation of the cue conflict test from Cheng (1986). Individual rats were trained to find food at one corner (as indicated by the black circle) of the rectangular enclosure in which distinctive wall panels were located at each corner (top). During conflict testing (bottom) each panel is relocated to the next corner clockwise thus placing it in an incorrect geometric corner relative to where it had been during training. Despite the relocation of the seemingly more salient featural cues to another corner, rats continued to choose the two geometrically correct corners (black circles).

In 1994, Hermer and Spelke further showed the influence that environmental geometry could have during reorientation, this time with young pre-linguistic children as subjects. Disoriented children were trained to search for a toy hidden at one corner of a rectangular space in which one of the walls was blue and the other three were white (see *Figure 1-3*). Importantly, the single blue wall provided the children with a featural cue with which they could use to localize the toy with their first choice on each trial. The children were disoriented before each trial (they were spun slowly in a circle with their eyes closed) and then asked to go to the corner in which they had seen the toy hidden previously. Strikingly, the behaviour of the children showed that they could search at the correct geometric corners – thus showing geometric encoding - but could not use the blue wall to disambiguate the correct corner from its geometric twin, evidence that they had not encoded the blue wall as a useable featural cue, a finding that contrasted with that of adults who had been trained with the same task (Hermer & Spelke, 1994; Hermer & Spelke, 1996).
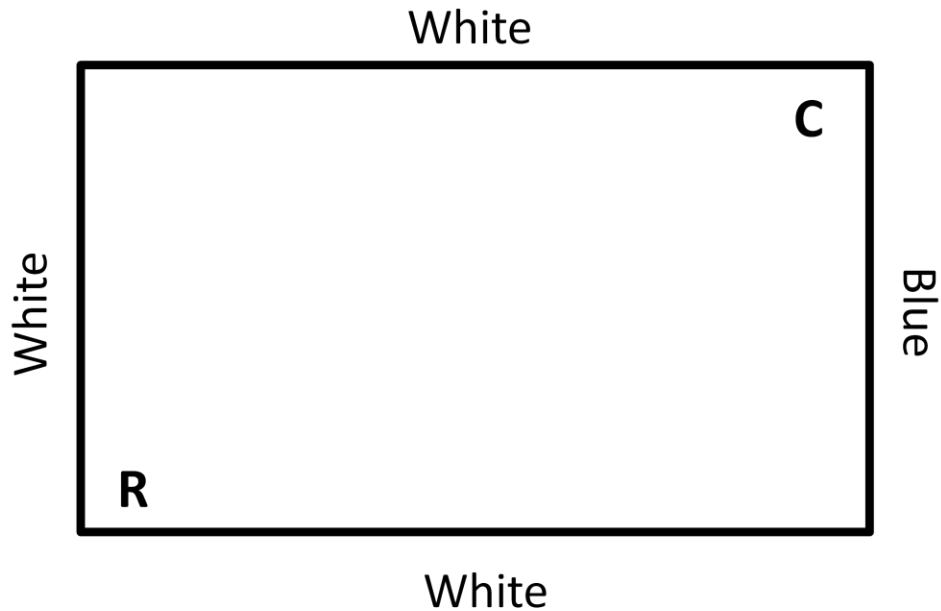
Figure 1-3 A schematic representation of the room used by Hermer and Spelke (1994). Three of the walls were white and one wall was blue. Children were trained to search at the correct corner "C" for a toy they had seen hidden there prior. Following disorientation the children primarily searched at corner "C" as often as they searched at corner "R" showing they had encoded the geometry of the space but could not use the blue wall to localize the correct corner.

The combination of Cheng's reorientation research with rats and Hermer and Spelke's reorientation research with children thus provided compelling evidence for the theory of a dedicated and impenetrable geometric module (Cheng, 1986; Gallistel, 1990). This theory posited that geometric spatial cues were unique in that they were encoded and processed within an encapsulated module separate from that of featural encoding, although featural cues could be later added to this geometric framework. As shown by the research with children, in humans the ability to conjoin features and geometry must occur later in development. It was presumed that the joining of featural and geometric cues in humans coincided with the development of language, including spatial language such as "left" and "right" (Shusterman & Spelke, 2005).

However, this conclusion remains controversial (Ratliff & Newcombe, 2008; Twyman & Newcombe, 2009).

The geometric module theory provided a valuable springboard for further research into the nature of featural and geometric learning in human and non-human animals. This research proved particularly compelling due to the heavily comparative nature of the studies that were conducted. Using a paradigm similar to that of Cheng (1986), geometric encoding of a rectangular space has since been established in a wide range of species including pigeons (Kelly, Spetch, & Heth, 1998), domestic chicks (Vallortigara, Zanforlin, and Pasti, 1990), rhesus monkeys (Gouteux, Thinus-Blanc, & Vauclair, 2001), fish (Sovrano, Bisazza, and Vallortigara, 2002), and even invertebrates (Wystrach & Beugnon, 2009). Indeed, the sheer scope of this research has been successfully used to show that reorientation through use of the geometric shape of the environment is a common ability shared by many different species. However, contrary to the modular theory of geometric encoding, and unlike the rats of Cheng (1986), many of the species tested were able to easily use the features to reorient. The fact that nonhuman animals could learn to integrate features and geometry argues against the need for language as a necessary component for conjoining these cues.

A second challenge to the modular theory came from developmental research with young children similar in age to the pre-language children who participated in the study by Hermer and Spelke (1994). In this case it was found that, although the children could not use a distinctively coloured wall to localize the correct corner in a small room (4 ft x 6 ft), they could however accomplish this task in a larger room [(8 ft x 12 ft) (Learmonth, Newcombe, & Huttenlocher, 2001)]. It has since been suggested that the enhanced use of featural cues by children in larger spaces but not smaller spaces reflects the need for featural cues to be more distal to be effective

(Learmonth, Newcombe, Sheridan, & Jones, 2008). This importance of environmental size has

subsequently been shown in other species including domestic chicks (Chiandetti, Regolin,

Sovrano, & Vallortigara, 2007) and fish (Sovrano, Bisazza, & Vallortigara, 2007). It would

seem unlikely then that the crucial joining of featural cues with geometric cues within a

dedicated and impenetrable geometric module would be so highly sensitive to a simple change in

room size (Twyman, Friedman, & Spetch, 2007).

As a result of the increasing amount of research leaning away from the prospect of an

impenetrable geometric module, support for the theory has slowly waned, indeed to the point

where even its earliest proponent has expressed substantial doubts as to its existence (Cheng,

2008). However, unlikely as it may be that geometric encoding occurs in a strictly modular

fashion, this still does not take away the near ubiquitous use of geometry by human and

nonhuman animals as a cue for reorientation. Therefore, the question remains, how is

environmental geometry learned and is this learning fundamentally different from that of

features? A problem with the research conducted thus far is that, while it has been very effective

at identifying the extensive use of geometric cues, it does not directly address the specific

geometric properties that are being encoded. A further limitation evident in the current body of

research has been the overwhelming dependence upon environments in which the geometric

information has been restricted to differential lengths of walls only. It has only been through the

use of geometric environments containing differential corner angles that potential cue-dependent

differences in geometric learning have gained prominence.

In research conducted by Pearce, Good, Jones, and McGregor (2004) rats were trained in

a modified version of the Morris water maze to find a hidden platform at either of the two

corners of a kite-shaped pool that projected 90° angles (see *Figure 1-4*). Within a kite-shaped

space when the two corners projecting 90° angles are, along with their adjoining walls, placed

side by side, together they make up the shape of a rectangle. When rats were subsequently tested

in a rectangular-shaped pool they searched predominantly for the hidden platform at a corner that

preserved the correct wall information in which they had learned to approach during training.

That is, if they learned to find the platform at the 90° corner containing a long wall to the left and

a short wall to the right in the kite-shaped environment, they searched at the two corners in the

rectangle that preserved these same properties. The researchers concluded that the rats had

encoded the *local geometry* of the kite and then transferred this information to the rectangle,

suggesting that the overall *global geometry* of the space could instead be perceived geometrically

through its local constituent parts.
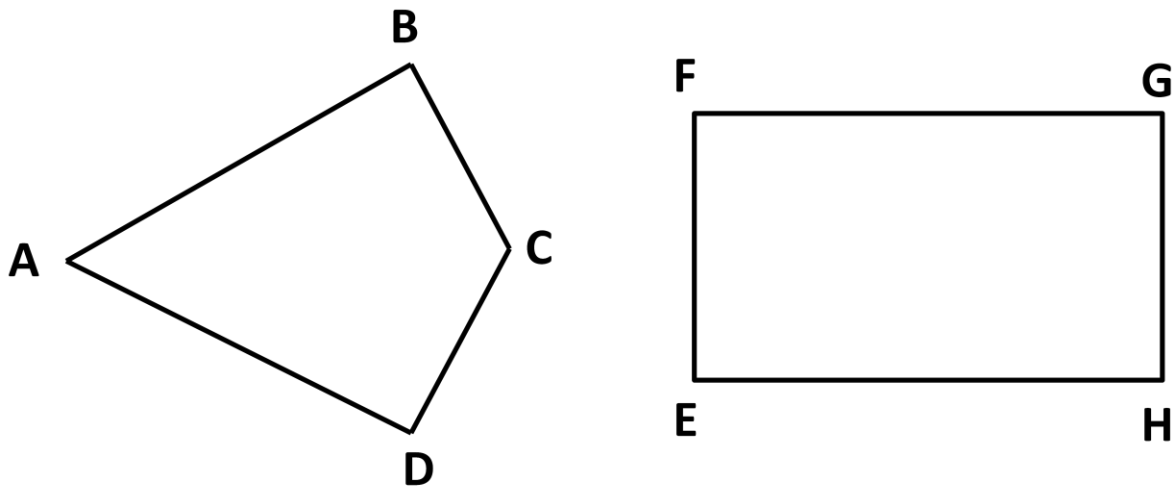
Figure 1-4 A schematic representation of the enclosure shapes used by Pearce, Good, Jones, & McGregor (2004). On the left is the kite-shape water maze used during training and on the right is the rectangular-shape water maze during testing. Rats were able to learn the *local geometry* from the kite and transfer this knowledge to the rectangle during testing. For example, in the kite rats learned to find the hidden platform at corner B where there was a long wall left and a short wall right. In subsequent testing in the rectangle these rats focused their searching for the hidden platform at corners E and G equally as often since these corners possessed the same geometric properties as corner B in the kite. Conversely, rats trained to search at corner D in the kite later directed their searches in the rectangle at corners F and H.

The water maze research conducted by Pearce et al. (2004) showed that the local geometry of an environment could be encoded and used independent of the global geometry. However, what was not known from this research was whether there could be a difference in learning one type of local geometric cue from another. In a study conducted by Tommasi and Polli (2004), domestic chicks were trained to find a food reward at one corner of a parallelogram-shaped enclosure (see *Figure 1-5*). Just as in a rectangle, a parallelogram contains differential lengths of walls such that diagonally opposite corners are geometrically identical in this regard. However, in addition to different wall lengths, a parallelogram also contains two different sizes of corner angles: one set of diagonally opposite corners projecting 60° angles and the other set projecting 120° angles. During testing with a rhombus-shaped enclosure the chicks showed that they could use either the global geometry (length of walls) or the local geometry (angles) to determine the correct geometric corner in which the reward was located. During conflict testing they were provided with a choice between either the angles or the walls as their preferred cue. Interestingly, the chicks that had been trained to search at a corner containing the smaller angle preferred to search at a corner that projected this same angle during conflict testing whereas the chicks trained to search at a corner containing the larger angle preferred the walls. The conclusion was that, for chicks, the smaller angles appeared to be more salient than the larger angles. The findings from Tommasi and Polli (2004) therefore pose the interesting possibility that certain local geometric cues may hold an encoding advantage over others.
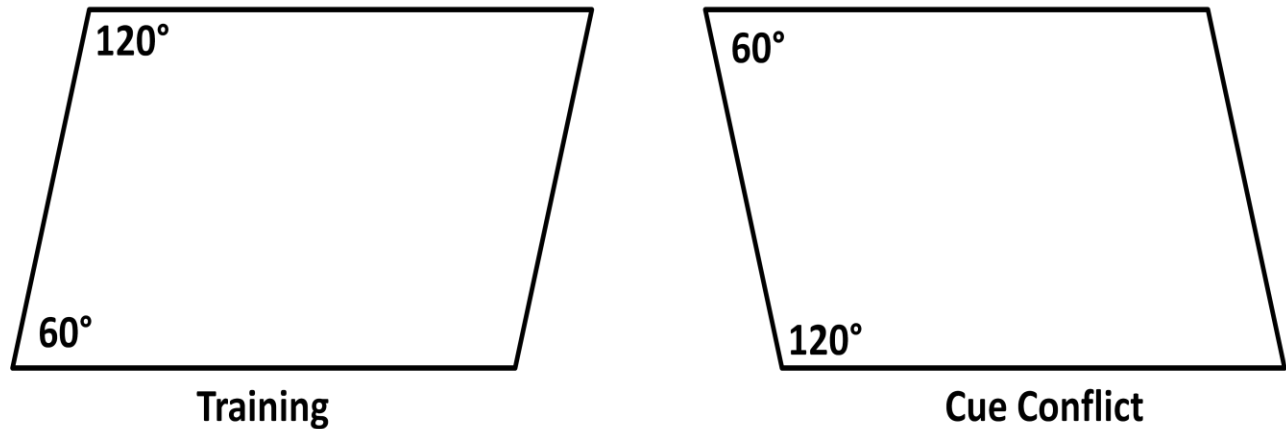
Figure 1-5 A schematic representation of the training and testing parallelogram-shape environments used by Tommasi and Polli (2004). During training (left) domestic chicks were trained to find food hidden at one corner of the enclosure. One set of diagonally opposite and identical corners contained either a) a corner angle of 60° and a long wall to the left of a short wall, or b) a corner angle of 120° and a short wall to the left of a long wall. During the cue conflict test (right) these angle-wall relationships were reversed, thus allowing the chicks to choose either the corner angles or the walls as their preferred cue. Chicks trained to search at the small angle searched at corners that preserved this angle whereas chicks trained to search at corners containing the large angle searched at corners that preserved the correct wall lengths from training (i.e., all chicks chose a corner with a short wall to the left of a long wall).

Current Studies

The goal of the studies included in this thesis was to examine possible learning differences that may exist between smaller and larger geometric angles in a real-world laboratory-based environment (i.e., not virtual or computer-based) and to determine whether these differences impact the use of these different sized angles during a spatial task. Evidence showing differential learning of geometric angles based on angular amplitude would suggest that certain geometric properties can be learned in either absolute or relative terms. This type of finding would run contrary to the theory of the geometric module which posits a clear distinction

between featural and geometric cues since a geometric angle that is learned absolutely would in fact suggest more featural-like encoding of that angle.

One noticeable drawback from previous research that has examined the learning and use of geometric angles – and indeed of local geometry in general – has been that these cues have always been presented within the context of a walled environment (Pearce et al., 2004;Tommasi and Polli, 2004; Hupbach and Nadel, 2005). With this in mind, a valid criticism of this prior research is that the local geometry being presented is never truly separated from the overall global shape of the space. Conscious of this limitation, the studies contained within this thesis make this distinction by presenting all of the angular information in the form of discrete objects unbound by walls. The studies outlined in chapters 2 and 3 presented geometric angles in the form of a visual discrimination task, with Chapter 2 examining discrimination by pigeons and Chapter 3 examining discrimination by adult humans. In Chapter 4, the learning and use of local geometric angles by adult humans was further examined within the context of a spatial reorientation task.

Chapter 2

The goal of the study presented in Chapter 2 was to determine how pigeons learn to discriminate geometric angles that are presented to them in a laboratory setting as real-world (not virtual or computer-based) discrete objects. As indicated earlier, pigeons have been shown to readily conjoin features and geometry within search tasks as well as reorientation tasks (Spetch et al., 1997; Kelly, Spetch, & Heth, 1998). It is for this reason that pigeons were selected as subjects in the current experiment, as opposed to rats for example which have shown a heavier

reliance upon geometry at the expense of features in both reorientation (Cheng, 1986) as well as navigational-based tasks (Benhamou & Poucet, 1998).

There are two general ways in which geometric stimuli can be learned: *absolute* and *relational*. A stimulus that is learned absolutely is done so based upon its exact measureable qualities (e.g., one angle is 60° and a second angle is 120°) whereas relational learning of a stimulus is based upon how similar it is to comparable stimuli (e.g., a 60° angle is smaller than a 120° angle). Therefore, an angle learned absolutely will be perceived as unique and distinct from other angles whereas an angle learned relationally will be perceived as simply being smaller or larger than other angles. Since pigeons tend to show absolute learning patterns when discriminating between stimuli that vary along a single dimension, it would therefore be expected that they would also show absolute learning of both small and large geometric angles. However, if small angles and large angles are learned differently, as suggested by Tommasi and Polli (2004), it might be expected that an absolute learning pattern would exist for one size of angle but not the other. During training, pigeons learned to discriminate between two different angle sizes (60° or 120°) and then during testing were provided with a direct choice between this training angle and one of a range of test angles that were either smaller or larger than the training angle. Results were analyzed to determine whether learning patterns (either absolute or relative) were dependent upon the size of the training angle.

Chapter 3

Since adult humans, unlike pigeons, tend to show relational, rule-based learning on discrimination tasks that employ simple single-dimension stimuli, the goal of the experiments

contained within Chapter 3 was to determine whether humans would show differential learning patterns for small and large angles.

Chapter 3: Experiment 1. The same basic procedure that was used for the pigeons in Chapter 2 was also used for adult humans in this experiment with the only exception being the size of training angles used (50° and 75°). This change was made in order to examine finer discrimination between the training and test angles (the range of test angles here differed by 5° increments as opposed to Chapter 2 in which they differed by 10° increments).

Chapter 3: Experiment 2. The goal of Experiment 2 was twofold: 1) to determine the type of response pattern that adult humans would show when an obvious relational strategy was no longer made available to them, and 2) to determine the type of learning pattern they would exhibit when an even smaller angle (25°) was used as a training angle. Experiment 2 followed the same procedure as Experiment 1 except now three groups of participants were trained to choose one of three different training angles (25°, 50°, and 75°) and then tested with only two angles - their training angle and a test angle that was either smaller or larger than the training angle.

Chapter 4

The goal of the study in Chapter 4 was to examine how small and large geometric angles are used as spatial cues by adult humans within the context of a spatial reorientation task. For example, if smaller angles are learned using an absolute encoding strategy then they may be more salient as a result and subsequently be more useful as reorientation cues in comparison to larger angles. In Chapter 4, angles of the same amplitude as in Chapter 3 (Experiment 1) were presented as four discrete objects arrayed such their overall configuration formed the shape of a

rectangle. This type of object array paradigm was specifically chosen over a walled enclosure

paradigm in order to keep the angle properties separate from the continuity provided by walls

(i.e., maintain a clear separation between the local and global geometry).   Disoriented adult

humans were trained to find a reward hidden in front of one of the four objects with each object

projecting a different angle (either 50° or 75° - the same angles used in Experiment 1 of Chapter

3), and diagonally opposite angles projecting the same angle. During testing either the global

shape of the array or the local angle cues were manipulated and the effects of these

transformations on geometric learning were analyzed.

CHAPTER TWO

Pigeon Learning Patterns of Geometric Angles Differ Based On Angle Size

Introduction

In 1918 the gestalt psychologist Wolfgang Kohler proposed that animals learn to discriminate between stimuli by first making direct comparisons and then formulating general rules based upon these comparisons, a process called *transposition*. For example, consider an animal in an operant chamber that is presented with two grey squares on a touch screen and rewarded for responding to the square that is shaded darker (S+) than the other (S-). During subsequent testing when the animal is presented with squares of various shades of grey that are both lighter and darker than S+ and S- respectively, it reserves its highest response rate not to the square associated most directly with S+ as one might expect, but instead to a square shaded slightly darker than S+. From this example it might then be concluded that the animal has learned a *relative rule* based on its discrimination training between S+ and S-, specifically to always respond to the darker square. However, upon further reflection, a second explanation can also describe this result. Spence (1937) proposed that discrimination training between two different stimuli, whereby one is always rewarded (S+) and the other never rewarded (S-), results in an excitation gradient forming around S+ and an inhibition gradient forming around S-. This explanation offered by Spence is suggestive not of relative learning but instead of *absolute learning* whereby S+ has been encoded and remembered based upon its exact measureable properties (however, for an alternate interpretation, see Lazareva, Wasserman, & Young, 2005).

The notion that if S+ is learned absolutely it will prompt greater associative strength to be shifted to an exaggerated version of S+ at first seems paradoxical. The explanation offered by Spence (1937) for this apparent contradiction is one based on competing response gradients. As noted previously, Spence proposed an excitation gradient forming around S+ and an inhibition gradient around S-, which theoretically should result in the highest rate of responding being centered at S+ (and conversely the lowest at S-). However, since the gradient around S- is comparatively flatter than that around S+, the unequal interaction between the two causes a dual shift in the response pattern. This shift manifests itself in the highest rate of responding occurring at a novel test value slightly beyond S+ in the direction away from S- and the lowest rate of responding occurring at a value slightly beyond S- in the direction away from S+. This type of response pattern has come to be identified as *peak shift* (Hanson, 1959) and is generally considered to represent the *absolute learning* of a given stimulus.

A hallmark of peak shift is that, in addition to the focus of responding being displaced away from S+ (and concurrently away from S-) to a nearby value instead, there is a gradual reduction in responding to values that become increasingly more extreme. This truncated form of stimulus generalization presumably reflects the absolute nature of the learning that has occurred; that is, once a value becomes too extreme, even if it lies in the preferred direction away from S- (e.g., an even darker grey square), it is no longer sufficiently representative of S+ and consequently garners a reduced response. This has indeed been borne out in visual discrimination research, often with pigeons as subjects, using a range of disparate stimuli from light wavelength (Hanson, 1959), spatial position (Cheng, Spetch, & Johnson, 1997), and even face recognition (Spetch, Cheng, & Clifford, 2004). As well, when translated to real-world situations this peak shift response behaviour can make a good deal of ecological sense. For

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example, aposematic prey that are distasteful or otherwise undesirable to potential predators have evolved special coloration as a warning to this effect; however, for prey that exhibit a slightly enhanced version of this coloration – thus making them even more visually conspicuous to predators than their conspecifics - the probability of them being attacked is actually lessened, provided that their coloration does not deviate too far from the norm (Gamberale & Tullberg, 1996).

It would seem then that with regard to transposition and relational learning, what was once speculated by Kohler to be a widespread phenomenon of animal learning can instead be just as easily explained by means of absolute learning. An interesting real-world application for investigating this concept can be found in the field of spatial cognition, specifically the learning and use of environmental geometry. Geometric properties of an environment encompass aspects such as direction and distance, and within enclosed spaces include lengths of walls, as well as the angles formed at the junctions of those walls. Whether animals can learn to utilize geometric cues has been the subject of much research, with a general finding being that a wide variety of species demonstrate at least a basic ability to encode the geometry of their immediate environment, including pigeons (Kelly, Spetch, & Heth, 1998), chicks (Vallortigara, Zanforlin, and Pasti, 1990), fish (Sovrano, Bisazza, and Vallortigara, 2002), rhesus monkeys (Gouteux, Thinus-Blanc, & Vauclair, 2001), and ants (Wystrach & Beugnon, 2009), in addition to human children and adults (Hermer & Spelke, 1994). Although it is well established that animals are able to use environmental geometry it is not always clear the specific properties that are being learned or how.

One method of examining the differential learning of environmental geometry has been through the employment of a spatial search task whereby the size of the space is altered between

training and testing. Gray, Spetch, Kelly, and Nguyen (2004) trained pigeons to search at the geometric center of a square enclosure for a food item buried beneath a thin layer of wood shavings. Once the pigeons could reliably find the food they underwent intermittent testing in an expanded square enclosure that was double the size of the enclosure in which they were originally trained. If the pigeons had learned the initial task through absolute means they would have encoded the exact distance of the location of the hidden food from one or more of the walls or corners during training and then preserved this search distance to one of the walls or corners when placed in the larger arena. However, if the pigeons had instead learned the task by relational means they would have encoded the location of the hidden food as simply being in the center of the square shaped enclosure; even though the size of the space was enlarged during testing the geometric shape remained unchanged (i.e., it was still a square), meaning that a relational learning account would result in the majority of searches being confined to the center of the larger space. Interestingly, the results from expansion testing showed evidence for both types of learning in that, in some instances the pigeons searched at a location that maintained the exact distance to one of the walls that they had experienced during training (absolute learning) whereas at other times they searched in the geometric center of the larger square space (relational learning), a finding also consistent with that of domestic chicks (Tommasi & Vallortigara, 2001).

A second type of paradigm that has been effective in distinguishing absolute learning from relational learning has involved the use of object arrays. Objects within the environment (e.g., trees, rocks, etc) are commonly considered to be featural cues in that they convey distinctive information such as texture or color. However, when two or more objects are positioned relative to one another, the resulting spatial configuration shared by them becomes a geometric cue of its own. In research similar to that described above, pigeons were trained to

search for a hidden food reward buried in the center of an array of four identical objects configured in the shape of a square (Spetch et al., 1997). Just as in the walled environments employed by Gray et al. (2004) with pigeons and Tommasi and Vallortigara (2001) with chicks, the same training and testing conditions applied, only now the square shape of the space was defined not by walls but instead by the configuration of the object array. During testing when the array was doubled in size the pigeons confined their searches to locations that preserved the exact vector (i.e., distance and direction) to one of the objects that had existed during training, behaviour indicative of absolute learning only. Tellingly, the pigeons did not search in the center of the expanded array, suggesting that they had not encoded the configuration of objects in relational terms, findings similar to those found with marmoset monkeys (MacDonald, Spetch, Kelly, & Cheng, 2004), Clark's nutcrackers (Kelly, Kippenbrock, Templeton & Kamil, 2008; but see Kelly, 2010), and even young children (Spetch et al., 1997).

The disparate findings from expansion-based search paradigms illustrate two important points about absolute and relational geometric learning in animals: 1) animals are clearly capable of both absolute and relational learning of geometric spatial cues but that, 2) relational learning in particular may be contingent upon the context in which those cues are presented. When the geometric shape of the search space is defined by walls, animals are more able to utilize a relational strategy than when the search space is defined instead by an array of identical discrete objects. Taken together, these results suggest that the type of geometric learning that occurs in animals is sensitive to subtle changes in the manner in which the global environmental geometry is presented.

Whereas much is known about absolute and relational learning in animals as it pertains to global geometry, comparatively little is known about the potential influence brought about by

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changes in local geometry. In research conducted by Tommasi and Polli (2004), disoriented domestic chicks were trained to find food hidden in one corner of a parallelogram-shaped enclosure. The geometry of such a space affords two types of useable geometric cues: 1) the differential lengths of the walls at each of the corners such that diagonally opposite corners are equivalent in this regard and, 2) the corner angles produced at wall junctions such that one pair of corners project an identical acute angle (60°) and the other pair an identical obtuse angle (120°). Whereas shape manipulation of the space during testing revealed that the chicks could independently use either type of cue to reorient, conflict testing in which the chicks could freely choose either length of walls or corner angles as their preferred cue revealed an interesting result: chicks that had been trained to search at a corner projecting the larger angle preferred the walls but chicks trained to search at a corner containing the smaller angle preferred the angle. It was therefore concluded by the researchers that the smaller angle appeared to hold a greater degree of salience than the larger angle. A question that arises from these findings is whether smaller angles are subject to different learning mechanisms than larger angles? The current research directly addressed this question, using pigeons as subjects, by assessing the type of learning involved in visual discrimination between a 60° angle and a 120° angle presented in the form of free-standing objects during a real-world task.

Materials and Methods

Subjects

A total of twelve pigeons (*Columbia livia*) were divided into two groups, group 60 and group 120, with an equal number of males and females per group. Data was only used for

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pigeons that passed training and advanced to testing (n = 4 per group) – a total of four birds (3 from group 60 and 1 from group 120) failed to advance to testing. All pigeons were housed in individual cages within the same colony room and maintained at 85% of their free feeding weight on a diet of grains, maple peas, and corn with grit and water available ad libitum. The temperature in the colony room was consistently maintained at approximately 20° C with a 12 hr light/dark cycle starting with lights on at 7:00 AM.

Apparatus

The experiment was conducted inside a wooden enclosure housed inside a larger experimental room. The walls of the enclosure uniformly consisted of blue tarpaulin below a white cloth ceiling. The floor was covered in a layer of wood shavings approximately 2 cm thick. A main door located at the front of the enclosure allowed for easy access by a researcher and a smaller guillotine-style door built low into the center of the main door was used as an entrance door for the pigeons. The inside of the enclosure was diffusely lit by two fluorescent bulbs situated above the cloth ceiling. A small nightlight was attached to the tarpaulin near the top of the back wall and was dark-sensitive such that it was automatically engaged whenever the main fluorescent bulbs were turned off; the purpose of the nightlight was to provide a minor source of illumination for a researcher upon entering the enclosure to retrieve a pigeon following a trial. Sound machines located outside the enclosure emitted white noise throughout all trials and served to block out external noises. A video camera fixed securely above the ceiling was used to record select trials with only the lens being visible from the inside through a small hole in the fabric.

The only items inside the enclosure were the two objects used to project the different angles. Each object consisted of two identical pieces of wood (each piece measured 30 cm high

x 20 cm wide) joined with a hinge such that the pieces could freely pivot to form a v-shape

angle. The objects (herein referred to as "angles") were each painted red and identical to one

another in every way. The angles were always positioned 150 cm in front of the door and 100

cm apart from each other (see *Figure 2-1*).
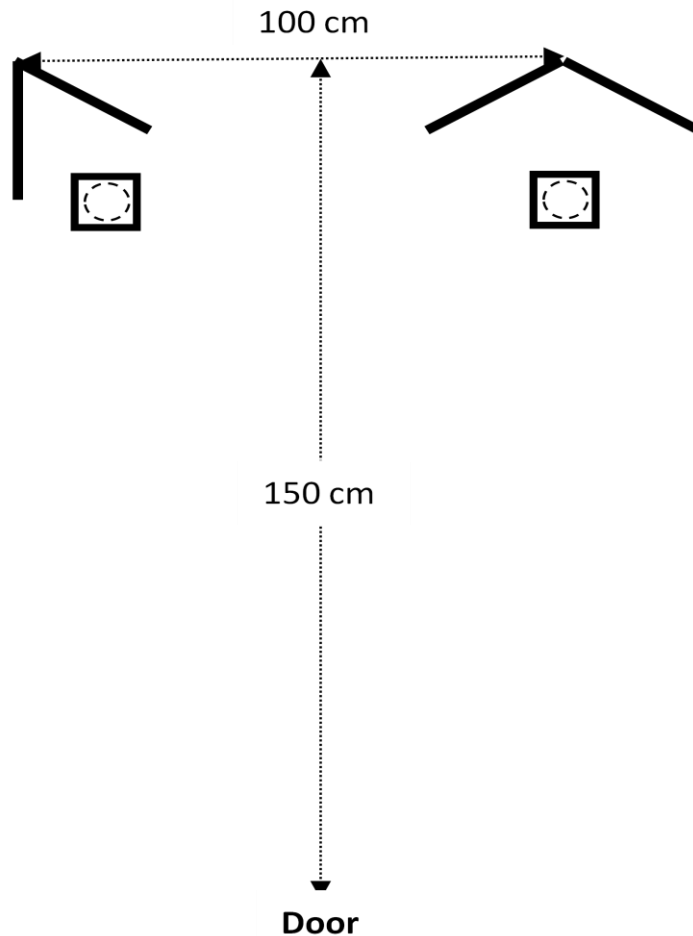
Figure 2-1: A schematic representation of the training setup. A pigeon was placed inside the enclosure via a sliding guillotine style door and the two angles were 150 cm in front of the starting position. The left object is set to 60° and the right to 120° in this illustration, although in the experiment these left-right assignments were pseudo-randomized and counterbalanced across a session. In front of each angle was a container (hashed circles) which was covered by a ceramic tile over paper towel which the pigeon had to displace in order to access the contents of the container. Only the container in front of a pigeon's positive angle was reinforced with food.

General Procedure

Each trial began with a researcher placing the pigeon inside the darkened enclosure through the guillotine sliding door. Once the pigeon was inside, the guillotine door was closed and the fluorescent lights were turned on, thus revealing the two angles at their assigned positions. In front of each angle was a tin container (8.5 cm diameter) with its opening fully covered by a piece of paper towel secured in place with elastic. Resting on top of each container was an identical white square ceramic tile which the pigeon learned to push aside with its beak and peck through the paper covering below. Once a pigeon made a choice and a trial was concluded (see training details for choice criterion) the lights were turned off and the nightlight at the back of the enclosure was engaged, whereby a researcher entered the enclosure and removed the pigeon, placing it inside a white opaque transport box located outside the enclosure where it remained between trials.

Habituation. The purpose of habituation was for the pigeons to become accustomed to removing the ceramic tile from the top of the container and pecking through the paper towel underneath in order to obtain the food inside. In the days prior to a pigeon starting the experiment a ceramic tile was placed on top of the food dish inside its home cage with the opening of the dish further covered with a piece of paper towel; once a pigeon had completed habituation trials during the experiment and advanced to training it no longer had its food dish covered. During habituation trials inside the experimental arena, the angles were absent and near the center of the enclosure there was a single paper-covered container with two maple peas inside and a ceramic tile placed on top. Once the pigeon was released inside the arena, it was allowed a maximum of twenty minutes to explore the space and find the maple peas located inside the container. If a pigeon failed to approach the container or was inactive during this

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period it was removed from the enclosure for approximately one half hour and a second trial started. Each pigeon received a maximum of five habituation trials daily. Once a pigeon could reliably obtain the maple peas training sessions began the following day.

Reinforced Training. All pigeons received one daily session five days/week with each session consisting of ten reinforced trials. During all training trials both angles were positioned inside the enclosure and one always projected a 60° and the other always projected 120°. The angle assignments were pseudo-randomized such that each angle appeared on the right and left side an equal number of times over the course of a session. Two maple peas were always placed inside the container in front of the given positive training angle (60° for group 60 and 120° for group 120). In order for a pigeon to choose an angle it had to use its beak to push away the ceramic tile from the container positioned in front of the angle and peck through the paper below. A choice was considered correct if the pigeon chose the container in front of its positive angle and consumed the food reward inside (herein referred to as a bird's "positive container"). If it did not choose the positive container with its first choice it was allowed to make a second choice. If needed, a pigeon was allowed a maximum of five minutes to find the food reward, although all pigeons learned to search for the food readily and consequently trials lasted no more than several seconds.

In order to facilitate learning during the initial training sessions, a piece of yellow construction paper was attached to the leftmost wooden panel of the positive angle, with the size of the yellow paper decreasing incrementally over sessions until it was no longer present. During the first stage of training the left panel of the positive angle was entirely covered in yellow paper, during the second stage it was reduced to half the original size, and during the third stage it was reduced to one quarter the original size. During the fourth training stage the

yellow paper was completely absent and the pigeons had to rely upon the angular information to guide choice behaviour. In order for a pigeon to reach criterion and advance to the next stage of training it had to choose correctly on eight out of ten trials for two consecutive sessions. Once a pigeon reached criterion during the fourth training stage it advanced to non-reinforced training.

Non-reinforced Training. Non-reinforced training sessions were identical to the fourth stage of training except that during three of the ten trials (never the first or the last) there was no food reward in either of the containers. During these non-reinforced trials a pigeon was allowed only one choice after which the lights were immediately extinguished and the pigeon removed from the enclosure. Once a pigeon reached criterion of eight out of ten correct choices over two consecutive sessions it advanced to testing. Pigeons that failed to reach criterion after fifty sessions were dropped from the experiment – a total of four pigeons (3 birds from group 60 and 1 bird from group 120) did not advance to testing.

Testing

Testing sessions were identical to non-reinforced training sessions in that only seven of the ten trials were reinforced (e.g., baseline trials to maintain accurate levels of responding). Of the three trials that were not reinforced, one was a control trial and the other two were test trials. Control trials were identical in every aspect to non-reinforced training trials (the two angles were always 60° and 120°) and were instituted in order to compare performance to test trials as well as to ensure that pigeons continued to choose their positive angle in the absence of reinforcement. During test trials, one of the angles was the positive angle and the other was a novel angle. There were a total of twelve novel angles presented during testing, ranging in 10° increments from the most acute angle of 30° to the most obtuse angle of 150°; all twelve test angles were

presented randomly without replacement over blocks of six sessions each, and there were four

blocks in total for a total of twenty-four test sessions. In total, all pigeons were presented with

each novel angle four times over the course of testing. Of the seven reinforced trials included in

each session, if a pigeon failed to maintain a criterion of at least five correct choices over two

consecutive sessions it was returned to non-reinforced training sessions. During this period it

was required to complete at least three sessions as well as achieve the training criterion eight out

of ten trials over two consecutive sessions before it could resume testing.

Results

This task appeared quite difficult for the pigeons to learn as one third of the birds failed

training. Given this failure rate, only four pigeons remained in each of the two groups. Thus, a

power analysis conducted using data from a similar study on the encoding of geometric cues by

birds (Chiandetti & Vallortigara, 2008) with standard error measure of .036 and an effect size of

.38 suggests that the power for the experiment was low (.289). Thus, although it is likely that

more subjects would be needed to draw strong conclusions from the data, the results are none-

the-less interesting as they suggest that the size of an angle may influence how it is relied up on a

spatial cue.

A p value criterion was set at .05 for all analyses and chance level responding was always

.50. Each group was first analyzed for the presence of an area shift and then a peak shift. For

the area shift analysis the mean proportion of choices to the three angles immediately below the

positive training angle were compared to the mean proportion of choices to the three angles

immediately above by a Wilcoxon signed ranks test. An area shift would exist if the mean

proportion of choices was comparatively higher to the three test angles in the direction away from S-; for group 60 these consisted of the three test angles immediately below 60° (i.e., 30°, 40°, and 50°) and for group 120 they consisted of the three test angles immediately above 120° (i.e., 130°, 140°, and 150°). For the peak analysis separate binomial tests were conducted for each of the test angles included above to determine if the proportion of choices to each angle exceeded what would be expected by chance.

Control Trials. In order to determine whether the birds maintained accuracy during control trials their mean response rates to their training angle was calculated and measured against chance responding of .50. For group 60, the response rate to the training angle (M = .836, *SEM* = .063) was significantly greater than what would be expected by chance (50%), t (3) = 5.32, p = .013; for group 120 the response rate to the training angle (M = .805, *SEM* = .067) was also greater than what would be expected by chance, t (3) = 4.52, p = .02. These results show that pigeons in both groups continued to respond accurately to their training angle during control trials throughout testing.

Group 60: Area Shift. The mean proportion of choices to the three angles immediately below 60° (M = .67, *SEM* = .084) was not significantly different than the mean proportion of choices to the three angles immediately above 60° (M = .41, *SEM* = .077), z = 1.56, p = .119, Wilcoxon signed ranks test. Although the birds showed a trend toward selecting test angles smaller than 60° compared to test angles slightly larger this difference did not reach significance.

Group 60: Peak Shift. Separate binomial tests were used to analyze the mean proportion of choices that pigeons made to each of the three test angles immediately above 60° and the three test angles immediately below. Of these angles only the mean proportion of choices to the 40°

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test angle exceeded what would be expected by chance, $p = .035$, binomial test; none of the mean proportion of choices to the other angles differed significantly from chance, $ps > .05$, binomial tests (see *Figure 2-2*). Taken together these results are suggestive of peak shift responding.
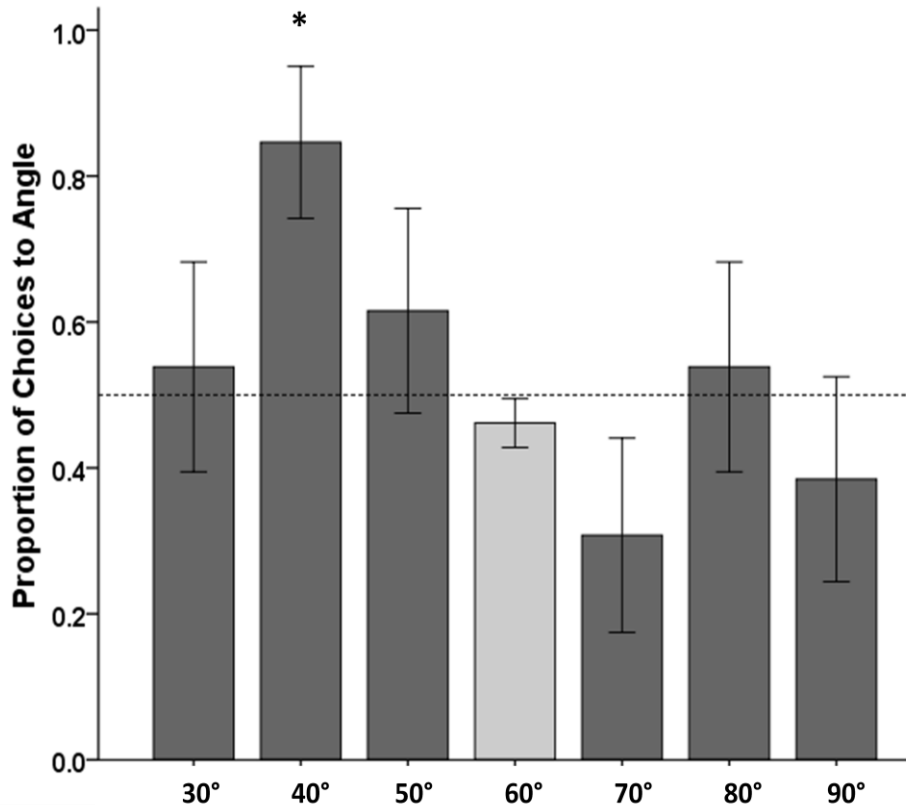
Figure 2-2: Results for group 60. There was not a significant area shift as the mean proportion of choices to the three angles below 60° did not differ significantly from the mean proportion of choices to the three test angles immediately above. The analyses of the individual test angles revealed a significantly higher proportion of choices only to the 40° test angle relative to chance, a finding consistent with a peak shift. Note that the light grey bar represents the mean proportion of choices to the training angle (60°) across testing with all angles indicated. *significant at $p <$ .05.

Group 120: Area Shift. The mean proportion of choices to the three angles immediately below 120° (M = .40, SEM = .067) was not significantly different than the mean proportion of choices to the three angles immediately above 120° (M = .60, SEM = .074), z = 1.67, p = .094, Wilcoxon signed ranks test. Although the birds chose the three test angles larger than 120° at a rate greater than they chose the three test angles immediately smaller than 120° this difference did not reach significance.

Group 120: Peak Shift. Separate binomial tests were used to analyze the mean proportion of choices that pigeons made to each of the three test angles immediately above 120° and the three test angles immediately below. Of these angles, in no case did the mean proportion of choices exceed what would be expected by chance, ps > .05, binomial tests (see *Figure 2-3*). Taken together, these results are not consistent with a peak shift.
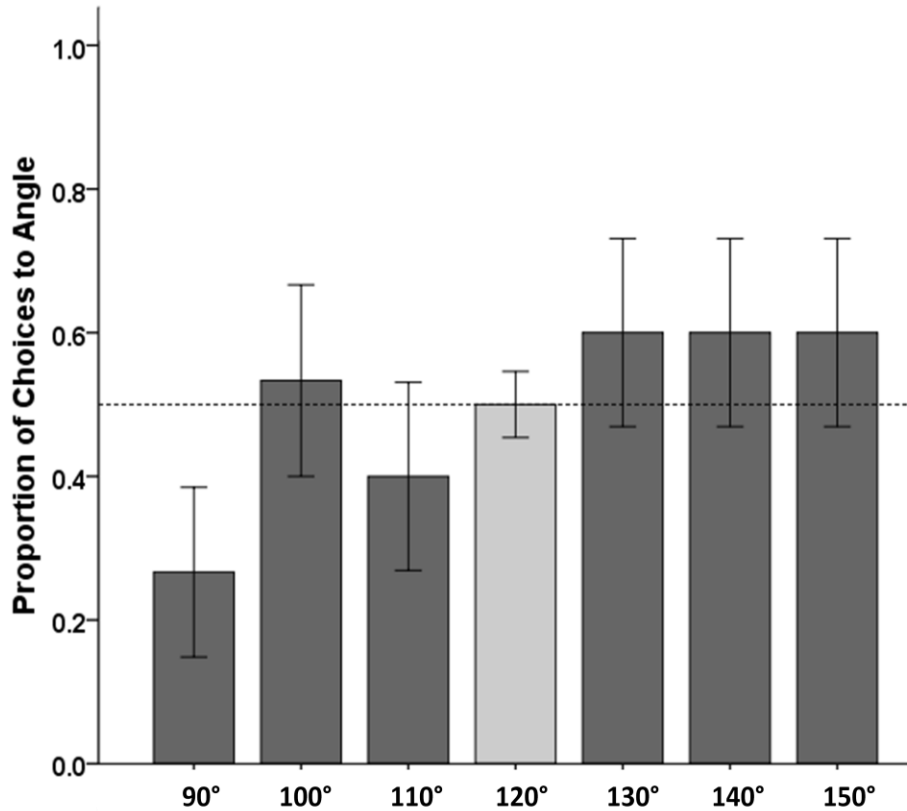
Figure 2-3: Results for group 120. The mean proportion of choices to each test angle did not exceed what would be expected by chance. Additionally, an area shift was not present as the mean proportion of choices to the three angles above 120° was not significantly different from mean choices to the three test angles immediately below. Note that the light grey bar represents the mean proportion of choices to the training angle (120°) across testing with all angles indicated.

Discussion

Pigeons were divided into two groups and trained to choose between a 60° angle and a

120° angle. During testing each pigeon was provided with a choice between its positive training

angle (either 60° or 120° depending on group assignment) and a novel test angle that was either

smaller or larger than the training angle. Results for pigeons trained on the smaller angle (group

60) is consistent with a peak shift response pattern, with the proportion of choices to the 40° test angle significantly greater than what would be expected by chance whereas this was not the case for either the 30° or 50° test angles. Conversely, the results for group 120 did not show a similar pattern, with none of the three test angles immediately above (or immediately below) 120° being chosen at a rate greater than would be expected by chance. These findings are suggestive of a more absolute pattern of responding for the smaller angle as compared to the larger angle.

The lack of an absolute response pattern for group 120 suggests that the 120° angle may have been more difficult for the pigeons to discriminate than the 60° angle. One reason that this might be the case is that the pigeons were using the edges of the wooden objects as a frame of reference to discriminate the angle sizes and as these edges moved further apart it may have become more difficult for the birds to make fine discriminations. Future experiments would benefit by using obtuse angles only as training angles to determine if accuracy changes as a function of angle size when both training angles are of a larger variety. If the encoding of angular information is dependent upon amplitude there may be a threshold (e.g., 90° perhaps) whereby learning becomes more difficult.

The results from group 60, which suggest absolute encoding, are consistent with the reorientation findings from Tommasi and Polli (2004) in which domestic chicks showed a preference for the 60° corners of a parallelogram over the larger 120° corners. The authors of that study suggested that the smaller angles may have been perceived by the chicks to be more salient than the larger angles. The current findings therefore contribute a possible learning account as to why an increase in salience would exist for a 60° angle over a 120° angle. Specifically, it may be that smaller angles are learned more absolutely – and therefore perceived as more distinctive – than larger angles. It is important to note also that the findings from

Tommasi and Polli (2004) resulted from angles that were presented in the form of corners bound by continuous walls whereas the current research used discrete objects. It could be argued that the current findings are based more purely on local angles since they are not an extension of a greater overall global space. An interesting future direction therefore would be to apply the current discrimination paradigm to a walled environment in order to specifically examine how continuous walls may influence the discrimination of geometric angles. For instance, birds could be trained on a similar discrimination task whereby one group of birds would learn to approach the two smaller (60°) angles of a parallelogram-shaped enclosure whereas another group of birds would learn to approach the two larger (120°) angles. Following training each group of birds would then be tested with larger and smaller pairs of angles. Would the presence of walls elicit a different pattern of results than was observed in the current study? As well, given that the current task appeared to be quite challenging for the birds to learn (a third of the birds failed to advance to testing), would the presence of walls facilitate angular discrimination learning?

The current task was surprisingly difficult for the birds to learn as evidenced by the number that failed to learn the task (3 from group 60, 1 from group 120). It is not clear why this was the case, although one possibility is that the distance separating the angles – the distance between possible choices (100 cm) -- was too short to deter to the pigeons from examining both containers. Increasing this distance might increase the response cost, encouraging the pigeons to choose more accurately. Another possibility is that the effort required by the pigeons to remove the single ceramic tile from the top of the container may also have not been enough of a response cost to encourage accurate responses. In research with Clark's nutcrackers it has been found that birds in experimental laboratory situations tend to search at less ideal cache locations than they normally would in the wild (Kamil, Balda, Olson, & Good, 1993). However, when the cost of

making such inefficient searches are made prohibitively more difficult – for example, by covering sand-filled cups with heavy items such as petri dishes that require the bird to remove them in order to investigate the contents of the cup - birds' choices become more efficient as a result of the extra effort involved in making a choice (Bednekoff & Balda, 1997). In future tasks of this type the distance between the angles should be extended while still allowing for the angles to be perceived from a similar straight-on perspective. As well, more than one tile could be placed on top of each container to provide a slightly heavier burden for the pigeons. A second potential problem could have been that the monochromatic red coloring of the objects may have made the angular information difficult to discriminate; adding featural enhancements (e.g., stripes) to both angles may allow for a more salient means of presenting this information.

Overall the current experiment suggests a difference in encoding strategies of geometric angles by pigeons. In particular, it suggests that smaller geometric angles show evidence of an absolute learning strategy whereas larger angles do not. These results indicate that the pigeons trained to choose the smaller of the two angles may have perceived this angle to be more distinct and thus less susceptible to wider generalization. In contrast, the pigeons trained to choose the larger angle did not show the same type of absolute response pattern, even though it was not clearly indicative of relational learning either. It appears then that the larger angles may have been more difficult for the pigeons to discriminate than the smaller angles, suggestive of the possibility that certain geometric cues that share the same intra-dimensional properties may nonetheless be subject to different types of learning mechanisms.

Future research should examine the discrimination of angular information using human participants since pigeons and humans show differences in using geometry during spatial tasks, with relational learning in particular being more easily accessible to humans than it is to pigeons.

From a practical sense, studying this question in humans would allow for a larger sample size than could possibly be examined using pigeons, therefore alleviating the problems that arise with low sample sizes – particularly when using a task that appears quite difficult to learn (at least for pigeons). As such, attrition through failure to learn the task could be dealt with by recruiting more individuals, whereas for pigeons this is a more difficult problem to overcome. It is for these reasons that conducting a similar type of angle discrimination experiment with adult humans makes both theoretical and practical sense.

CHAPTER THREE

Discrimination of Geometric Angles by Adult Humans

Introduction

Human and non-human animals routinely learn to discriminate between different types of environmental stimuli. Stimulus generalization happens when an organism responds to a specific stimulus but also to other stimuli that are closely similar. Whereas stimulus generalization is a necessary function for behaviours such as basic object and predator/prey recognition (Gamberale & Tullberg, 1996), it is also critical for spatial orientation and navigation by mobile organisms. A universal component of spatial navigation is the use of geometric properties such as length, distance, and direction, cues that are used to varying degrees by all spatially aware animals. Geometric cue learning can occur in two fundamentally different ways: *relative encoding* and *absolute encoding*. Absolute encoding implies that a particular geometric property (e.g., length of a wall) has been learned and encoded using an exact perceptual measure of that property. Relative encoding, however, indicates that a more general relational rule has been established during learning and it is this rule that governs subsequent spatial behaviour (e.g., the length of a wall is remembered as being shorter or longer than a nearby wall).

Whether learning of a geometric property occurs relatively or absolutely seems to depend upon the nature of the property itself as well as the manner in which it is presented. Consider a walled enclosure with a square shape in which an organism is trained to search for a hidden goal buried in the center of the space. During testing the enclosure is doubled in size, thereby expanding the available space while simultaneously preserving the overall square shape of the

environment. The purpose of this type of expansion is to test whether the original space has been encoded using relative or absolute metrics. If it has been encoded relatively then searching should be localized to the center of the enclosure since the relative center of a small or large square-shaped space remains constant regardless of the size change. However, if it has been encoded absolutely, then the distance from the center to the walls in the small enclosure will be transferred to the larger enclosure, resulting in a search pattern that maintains a distance and direction vector to any of the walls or corners. When Gray, Spetch, Kelly, & Nguyen (2004) trained pigeons to search for a food reward in the center of a square arena and then tested them in a square arena double the size, the pigeons exhibited evidence for both relative and absolute encoding of the space. That is, sometimes the pigeons searched in the center of the larger arena (relative encoding) and sometimes they searched at a distance from one of the walls that matched the same distance from the walls to the center in the smaller training arena (absolute encoding). This type of response pattern has also been shown when chicks were trained and tested using a similar paradigm (Tommasi & Vallortigara, 2001).

Similar research using object arrays rather than walled environments has yielded striking inter-species differences in the nature of geometric encoding. In this type of experiment the overall shape of the space is defined not by walls but instead by the positioning of discrete objects in relation to one another. Spetch et al (1997) trained both pigeons and humans to search in the center of an array of four identical objects positioned such that their overall configuration formed the shape of a square. When the array was expanded outward, thereby maintaining the same square configuration, the resulting species difference in search strategy became evident. Specifically, pigeons preserved the absolute direction and distance metrics between the objects and the goal location that they had learned during training and then used this information to

search near only one of the objects during testing. However, humans continued to search

exclusively in the center of the object array, thus relying upon a relative metric, specifically the

center of the overall square configuration. Similar research with table-top object arrays has

yielded congruous results, with a strong reliance upon absolute encoding by non-human animals

– in this case marmoset monkeys – compared to an almost complete reliance on relative

encoding by adult humans (MacDonald, Spetch, Kelly, & Cheng, 2004). Interestingly, the same

research showed that young children behaved more similarly in these tasks to non-human

animals than they did to human adults, suggesting that for humans this behaviour develops with

age (MacDonald et al 2004; Spetch and Parent 2006).

In addition to search tasks it is also well established that a wide range of species, humans

included, can use the geometric shape of an enclosed space as a cue for reorientation (see Cheng

and Newcombe 2005 for a review). A common reorientation paradigm involves the use of a

rectangular room or enclosure in which a disoriented organism is required to remember the

location of a reward previously hidden near one of the corners. Since adjacent walls of a

rectangle are of different lengths, this allows individual corners to be remembered based on the

geometric properties of the corners constructed from the adjoining walls, with diagonally

opposite corners sharing identical geometric information and thus appearing visually

indistinguishable. It has long been established that the geometric information provided by these

walls is sufficient for organisms to localize their searches to the two geometrically correct

corners (Cheng, 1986).

In addition to the lengths of walls, a second type of useable geometric information

available within enclosed spaces is the angles present at the corners. Although angular

information within a rectangular space is necessarily limited given that all the corners are 90°,

research using more geometrically informative spaces has demonstrated the value of corner

angles as an orienting cue. Tommasi and Polli (2004) trained chicks to search at one corner of a

parallelogram-shaped enclosure which, in addition to differential lengths of walls, also contained

corners with distinctive angles. Specifically, one pair of diagonally opposite corners projected

identical obtuse angles (120°) and the other pair of diagonally opposite corners projected

identical acute angles (60°). During test trials, when the shape of the space was converted to a

rhombus and therefore nullifying the wall information but preserving the angle information, the

chicks could still use the angles to reorient, showing that this information had been successfully

encoded during training. In related research with humans, children trained in a rhombus-shaped

space also learned to use corner angles to direct their searches to the geometrically correct

corners (Hupbach & Nadel, 2005). Although these experiments show that angles can indeed be

used by different organisms, they do not indicate the nature of the learning involved. Are the

angles being encoded relatively, in which case an organism would simply need to recognize that

one angle is smaller or larger than the other? Or are they being encoded absolutely, in which

case an organism would remember and recall the angles in a more precise manner? And finally,

does the type of encoding depend upon the size of the angle being learned?

Reichert and Kelly (2010, see Chapter 4 in this dissertation) trained and tested adult

humans on their ability to use angular cues during a spatial reorientation task. The unique aspect

of this research was that the angular cues were not part of an overall walled space, as is typically

the case, but instead were presented to participants in the form of a discrete object array (similar

to the object arrays discussed above). Four identical wooden objects were positioned such that

each object occupied one point of a four-point rectangle. Each object consisted of two identical

pieces of wood joined with a hinge such that they could expand or contract to form unique

angles. One pair of diagonally opposite objects was set at 50° and the other pair was set at 75°. During training, participants were required to learn the location of a reward (a coin) consistently hidden inside a container positioned in front of one of the objects, meaning that in order to remember the location of the reward participants could simply encode the angle of the object associated with that location. During testing when the object array was converted to a square and the angular information from training was still available, it was discovered that the smaller (50°) of the two angles proved to be a more reliable orienting cue than the larger angle (75°).

In order to better understand how different geometric angles are learned and encoded we used a real-world discrimination paradigm using objects that formed geometric angles. The design employed a discrimination task involving the same training angles (50° and 75°) previously used by Reichert and Kelly (2010) in a reorientation task, as well, the examination of this discrimination was extended in a second experiment during which a third angle (25°) was added in conjunction with the previous two angles. Human participants were trained to choose their rewarded training angle (S+) and to refrain from choosing the other two angles (S-). During testing, participants were presented with a choice between their training angle and a novel test angle. The novel angle presented was one of a set of 16 angles, thus allowing for the analyses of resulting response gradients. The pattern with which participants generalized their responses to novel test values was informative of the nature of the learning that had taken place. An *area shift* occurred if participants showed higher response rates to test values beyond S+ in the direction away from S- than they did to test values beyond S+ in the direction toward S- (Cheng & Spetch, 2002). A *peak shift* was a more specific type of generalization pattern in which peak responding was not at the S+ but instead at a nearby value(s) beyond S+ in the direction away from S- (Hanson, 1959). Even though the highest rate of responding occurred at a test value(s)

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displaced from S+ itself, a peak shift was still considered to be representative of an absolute learning pattern (Spence, 1937). Finally, if responses to extreme values in the shifted direction remained high relative to values nearer S+, then the pattern was less representative of peak shift and more representative of relative rule-based learning.

Experiment 1

The purpose of Experiment 1 was to assess the ability of men and women to discriminate among different angles and to identify what encoding strategies were being used. Individuals were required to discriminate between two different angles formed from wooden panels by choosing the angle associated with reward. One group of participants was rewarded for choosing the 50° angle and the other for choosing the 75° angle. After successful discrimination training, participants received non-reinforced test trials during which their rewarded training angle was presented alongside a novel angle and the participants had to choose which angle they thought was correct (i.e., which one had been previously associated with reinforcement).

Materials and Methods

Participants

A total of 64 first-year University of Saskatchewan students (Age = 19.5 years) participated in this study in exchange for course credit. Participants were randomly assigned to one of two groups, with individuals in group 50 reinforced for choosing the 50° angle during training and individuals in group 75 reinforced for choosing the 75° angle during training. An

equal number of men and women were assigned to each group. There were 3 men and 5 women

who failed to pass training and they were replaced by a new participant of the same gender to as

to maintain an equal number of men and women per group (N = 56; 14 men, 14 women per

group).

Apparatus

Two objects were positioned within a larger experimental room (570 cm long x 275 cm

wide x 270 cm high with all the walls covered by identical opaque curtains). Each object

consisted of two uniformly identical pieces of wood (each piece of wood was 30 cm wide x 1.5

cm deep x 60 cm high) joined together with a hinge so that the pieces could expand or contract to

form an angle – herein these objects are referred to as "angles". A blue coloured stripe (4 cm

wide) was located along the top edge of each wooden piece, and a second blue stripe was located

26 cm below the first. In addition, two red coloured stripes (2 cm wide) were located, one 4 cm

from the top edge and a second 36 cm from the top edge of each wooden piece. Each coloured

stripe spanned the entire width of the wooden piece. The floor of the room was covered in

shredded paper to remove any extraneous visual cues. The angles were positioned in the center

of the room, 150 cm apart from each other. Located in front of the angles were two identical tin

containers (8.5 cm diameter), covered by identical brown plastic lids. A start position was

clearly marked on the floor near the entrance of the room and located a distance of 250 cm in

front of the two centrally placed angles (see *Figure 3-1*).
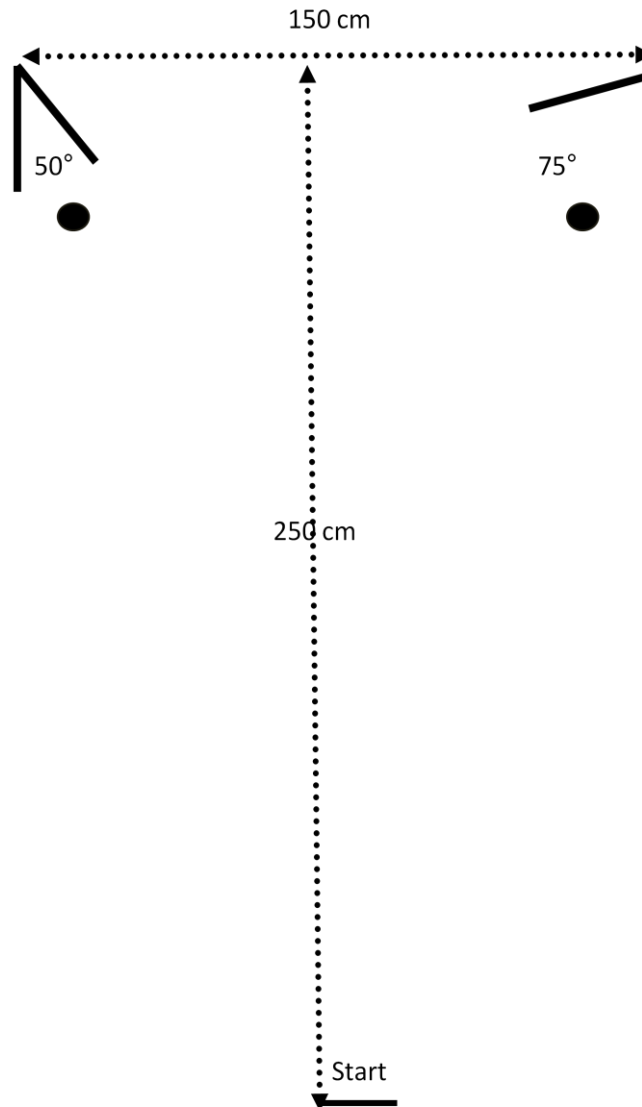
Figure 3-1: A schematic top-down representation showing the positioning of the two objects during training and testing in Experiment 1. On the left is the object projecting the 50° angle and on the right is the object projecting the 75° angle - note that this left-right placement of the angles was counterbalanced. The dark circles in front of each angle represent the identical covered tin containers. Depending upon group assignment (either Group 50° or Group 75°) a coin was located inside only one of the containers during training only. A trial always began with the participant approaching the angles from the start position.

Training

During training one angle was set to 50° and the other was set to 75° and the specific

objects used to make these angles was randomized between trials (i.e., each object was used to

create the 50° and 75° angle). Furthermore, the positioning of the different angles either on the

left or right was counterbalanced. Prior to beginning the experiment participants were provided

with verbal instructions in a room separate from the experimental room. They were informed

that inside the experimental room they would see two tin containers and their goal was to locate

the one in which a reward (a coin) was hidden. They were allowed two choices to locate the

container with the coin (herein referred to as the "correct container"), but were encouraged to be

as efficient as possible and try to locate the coin with their first choice. There was no mention of

objects or the presence of any other cues that might aid them in their decision-making. All

participants were trained and tested individually.

Each trial began with the participant entering the experimental room and standing at the

start position which was clearly marked on the floor near the entrance. An experimenter

standing nearby instructed him/her to make their choice when ready. In order to choose a

container the participant walked up to it, picked it up, and shook it to determine if the coin was

inside (the lid did not have to be removed). If the participant did not locate the correct container

on the first attempt another choice was allowed to locate the hidden coin. A participant was

credited with a correct response during a trial only if they found the coin on their first attempt.

Once they had located the correct container the participant exited the room while the

experimenter prepared the angles and containers for the next trial. All trials were manually

scored by the experimenter inside the room as well as recorded via a camera secured in the

ceiling (the camera was connected to a Sony DVR located in the adjacent room). Training

consisted of a total of 12 trials and participants were required to respond correctly on the last two trials in order to pass training. Testing results were only considered for participants who successfully passed training.

Testing

Similar to training, during testing only two angles were available for a participant to choose between. The testing phase consisted of a total of 24 trials and there were three types of trials conducted: *baseline trials, control trials*, and *test trials*. Baseline trials (6 in total) were identical to training trials in every respect, with a 50° angle and a 75° angle available, and a participant was rewarded for choosing the correct container associated with their assigned training angle. Control trials (6 in total) were identical to baseline trials except: a) participants were allowed only one choice, b) trials were non-reinforced, meaning no coin was available in either container and, c) a choice consisted of the participant approaching the container (and corresponding angle) of their choice and, rather than picking up the container they thought was correct, they pointed to it. The purpose of baseline trials was for participants to continue to associate their positive angle to reinforcement throughout the testing phase; the purpose of control trials was to determine whether the absence of reinforcement affected the participants' choices. Test trials (12 in total) were identical to control trials except that a novel angle replaced the non-reinforced angle (the correct training angle remained). The 12 novel angles ranged in increments of 5° from the smallest angle of 30° to the largest angle of 95° . The order of presentation of the test angles was randomized for every participant and each angle was experienced only once per participant throughout testing. Therefore, test trials always provided participants with a direct choice between their correct training angle and a novel angle. The

baseline and control trials were interspersed pseudo-randomly between test trials with the

condition that neither trial of the same type was conducted on consecutive trials.

Results Experiment 1

All trials were recorded and participant choices were re-scored by a second researcher

naive to the hypotheses of the experiment; inter-rater reliability between the two researchers was

100%. Choices made during testing were analyzed to determine the nature of the response

gradients for both group 50 and group 75. Each test trial involved a direct choice between the

training angle (S+) and a novel test angle. In order to test for the presence of an area shift for the

group of test angles either immediately above or below S+ separate Wilcoxon signed ranks tests

were conducted for both groups; separate Wilcoxon signed ranks tests were also conducted for

each group comparing the two shifted angles closest to S+ with the two shifted test angles

furthest away. To compare the proportion of choices to S+ versus individual test angles separate

binomial tests were conducted. A *p* value criterion of .05 was used for all statistical tests and

chance responding was .50 for all tests.

Control Test Accuracy. Control trials were identical to training trials except they were

non-reinforced. To examine whether participants continued to respond accurately to their

training angle across control trials a separate Friedman's analysis was conducted for each group.

The results of the test showed no significant difference for control accuracy across trials for

group 50 ($M = .99$, $SEM = .006$), $X^2(5) = 5.00$, $p = .419$ or for group 75 ($M = .99$, $SEM = .006$),

$X^2(5) = 5.00$, $p = .419$. To determine whether control accuracy was maintained throughout

testing separate binomial tests were conducted for each group. Results showed that choice

accuracy for group 50 (*M* = .96, *SEM* = .006) was significantly greater than what would be

expected by chance, *p* < .001, binomial test; results for group 75 (*M* = .96, *SEM* = .006) also

showed that accuracy was significantly greater than what would be expected by chance, *p* < .001,

binomial test. Overall, accuracy on control trials remained near ceiling.

Area Shift: Group 50 and Group 75. In order to determine the presence of an area shift

for either Group 50 or Group 75 a Wilcoxon signed ranks test was conducted comparing the

mean proportion of choices to the four angles immediately above S+ with the four angles

immediately below S+. For Group 50, the mean proportion of choices (*M* = .79, *SEM* = .069)

was greater for the four test angles immediately below 50° (30°, 35°, 40° and 45°) compared to

the mean proportion of choices (*M* = .11, *SEM* = .037) to the four angles immediately above 50°

(55°, 60°, 65° and 70°), *z* = 4.29, *p* < .001. Similarly, for Group 75, the mean proportion of

choices (*M* = .87, *SEM* = .049) was greater for the four test angles immediately above 75° (80°,

85°, 90° and 95°) compared to the mean proportion of choices (*M* = .07, *SEM* = .025) to the four

angles immediately below 75° (55°, 60°, 65° and 70°), *z* = 4.64, *p* < .001. These results are

consistent with an area shift for both groups, with participants in Group 50 preferring the test

angles immediately below 50 compared to test angles immediately above 50. Conversely,

participants in Group 75 showed a similar pattern but in the opposite direction, with a greater

proportion of choices to the test angles immediately above 75° compared to the four angles

immediately below 75°.

Peak Shift Analysis: Group 50. Although these area shifts indicate that the participants

in each group were showing similar choice responses to small angles (group 50) or large angles

(group 75), analysing the data for an area shift does not provide information as to whether the

participants were showing different choices among the smaller or larger angles. Thus, the data

were further analyzed to determine whether, within the area shift, there would be evidence of a peak shift. In order for an area shift to be considered a true peak shift two conditions had to be met: 1) choice responding to the two test values closest to S+ in the shifted direction (S+Near) must have been significantly greater than choice responding to S+, and 2) choice responding to the two closest values (S+Near) must have been significantly greater than choice responding to the two extreme values in the shifted direction (S+Far). Depending upon the group, either the two smallest or two largest test angles represented S+Far (30° and 35° for group 50 and 90° and 95° for group 75). For S+Near, the two test angles beyond S+ in the shifted direction were used (40° and 45° for group 50 and 80° and 85° for group 75).

Since each test trial involved a choice between two angles (S+ and a novel test angle) separate binomial tests were conducted to determine whether the proportion of choices to each of the two test angles individually associated with S+Near and S+Far exceeded chance responding. For group 50, the proportion of responses to the two S+Near test angles were each greater than what would be expected by chance, (chance = 0.50; 45°: M = .82, SEM = .074; 40°: M = .86, SEM = .067, p = .001 and p < .001 respectively, binomial tests). Also for group 50, the proportion of responses to each of the two S+Far test angles exceeded what would be expected by chance, (35°: M = .75, SEM = .083; 30°: M = .71, SEM = .087, p = .013 and p = .036 respectively, binomial tests).

In order to determine whether the two test angles comprising either S+Near or S+Far showed similar rates of responding and thus could be grouped, separate Wilcoxon signed ranked tests were conducted for each pair, with results showing that the proportion of choices was not significantly different in either case (S+Far: z = .577, p = .564; S+Near: z = .577, p = .564). A subsequent Wilcoxon signed ranks test for group 50 showed that the difference in mean

proportional responding between S+Near (45° and 40° test angles combined: $M = .84$, $SEM =$ .063) and S+Far (35° and 30° test angles combined: $M = .73$, $SEM = .079$) was significant, $z = 2.45$, $p = .014$.

Taken together, these results are partially supportive of a peak shift pattern of responding for Group 50. Whereas the proportion of choices exceeded chance responding for each of four test angles in the shifted direction (i.e., smaller than 50°), there was a significant decrease in the proportion of choices from S+Near to S+Far, revealing a stronger bias toward the two test angles closer to 50° than the two furthest away (see *Figure 3-2*).
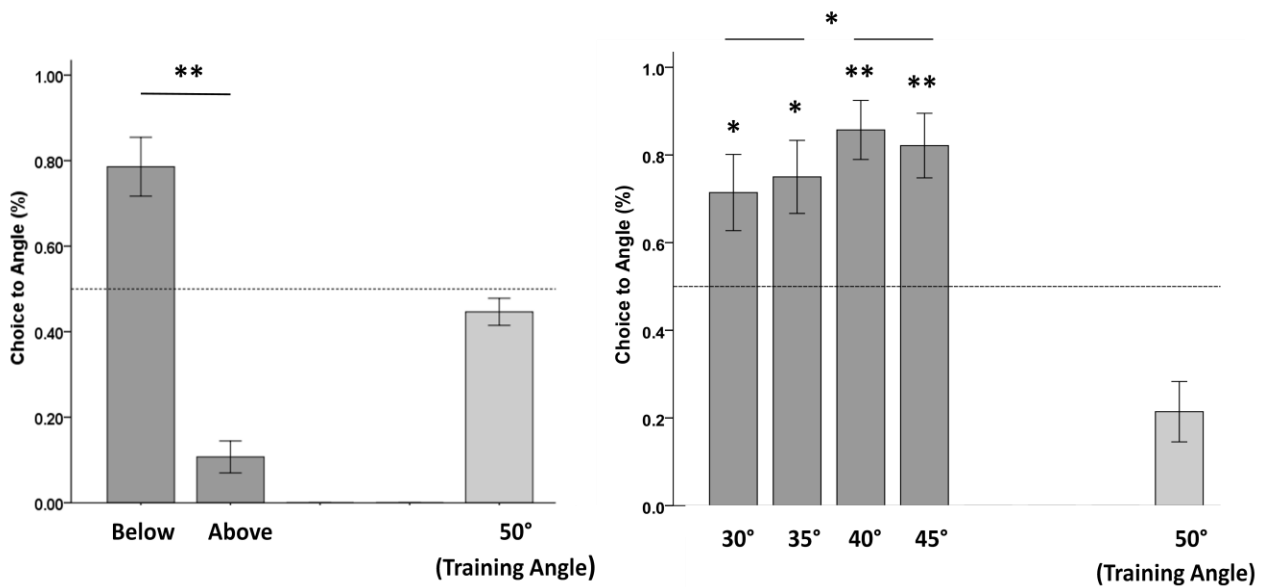
Figure 3-2*: The leftmost figure shows the area shift for group 50 with the mean proportion of choices to the four test angles below 50° (S+) significantly greater than the mean proportion of choices to the four test angles immediately above 50°. The lighter bar to the right represents the mean proportion of choices to 50° when directly pitted against the test angles indicated. The rightmost figure shows that the mean proportion of choices was significantly greater than chance for each of the four smallest test angles when individually pitted against 50°. The mean proportion of choices to the two test angles comprising S+Near was also significantly higher than the mean proportion of choices to the two test angles comprising S+Far. The lighter bar to the right represents the mean proportion of choices to 50° over the course of testing with the angles indicated. Together these results show an area shift favouring smaller angles for group 50 and partial support for a peak shift also. *Significant at $p < .05$, **Significant at $p < .001$.

Peak Shift Analysis: Group 75. For Group 75, the proportion of responses to each of the two S+Near test angles were each significantly greater than what would be expected by chance (chance = 0.50; 80°: M = .82, SEM = .074; 85°: M = .89, SEM = .060, p = .001 and $p < .001$ respectively, binomial tests). For S+Far, the proportion of responses to each of the two test angles were also each significantly greater than what would be expected by chance (90°: M = .86, SEM = .067; 95°: M = .89, SEM = .060; $ps < .001$, binomial tests).

In order to determine whether the two test angles comprising either S+Near or S+Far showed similar rates of responding and thus could be grouped, separate Wilcoxon signed ranked tests were conducted for each pair, with results showing that the proportion of choices was not significantly different in either case (S+Near: z = 1.00, p = .317; S+Far: z = .447, p = .655). A subsequent Wilcoxon signed ranks test showed no significant difference in proportional mean responding between S+Near (80° and 85 ° combined: M = .86, SEM = .057) and S+Far (90° and 95° combined: M = .88, SEM = .049), z = - .447, p = .655.

Overall the results for group 75 are fully supportive of an area shift pattern of responding and not a peak shift since there was no significant difference between the proportion of choices made to the test angles closest to the training angle of 75° in the shifted direction (S+Near) versus the test angles furthest away [(S+Far) (see *Figure 3-3*].
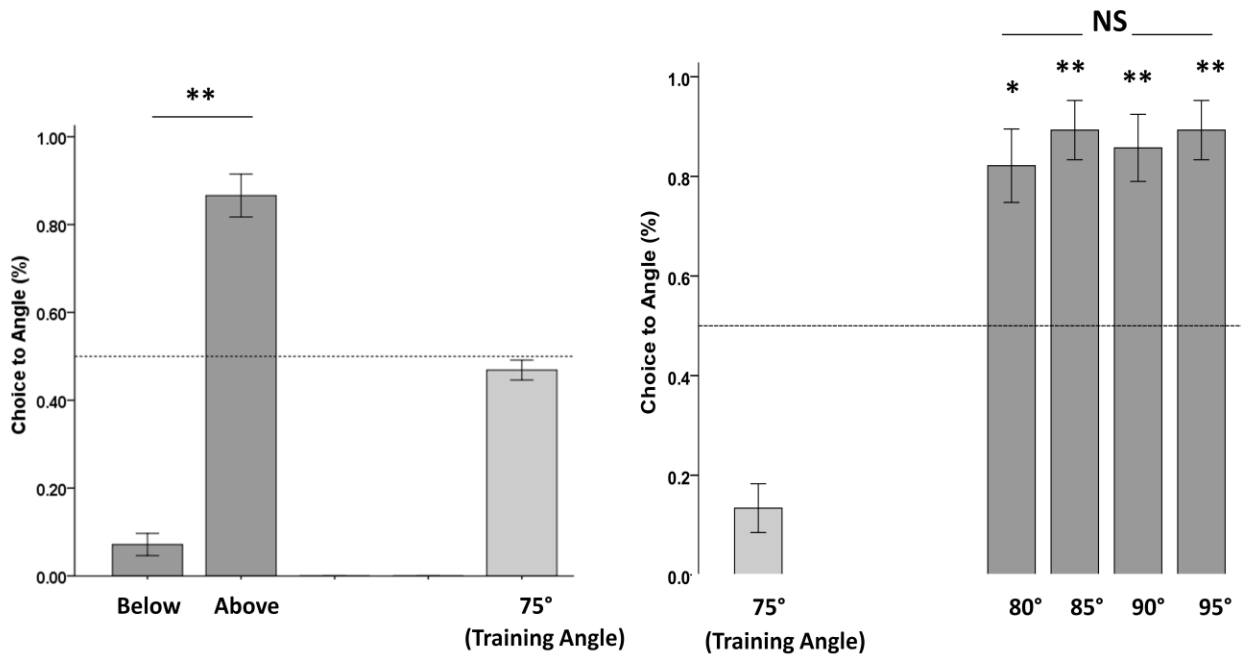
Figure 3-3: The leftmost figure shows the area shift for group 75 with the mean proportion of choices to the four test angles above 75° (S+) significantly greater than the mean proportion of choices to the four test angles immediately below 75°. The lighter bar to the right represents the mean proportion of choices to 75° when directly pitted against the test angles indicated. The rightmost figure shows that the proportion of choices was significantly greater than chance for each of the four largest test angles when individually pitted against 75°. The mean proportion of choices to the two test angles comprising S+Near was not significantly different from the mean proportion of choices to the two test angles comprising S+Far. The lighter bar to the left represents the mean proportion of choices to 75° when directly paired against the test angles indicated. Together these results are supportive of an area shift only for group 75. *Significant at $p < .05$, **Significant at $p < .001$.

Discussion Experiment 1

Adult humans were first trained to accurately respond to one of two different size angles (either 50° or 75°) projected by objects located within a larger experimental room. Following training they were tested with a range of novel angles in conjunction with their training angle and required to choose (in the absence of reinforcement) the angle which they considered to be correct. Results showed that participants generalized their responses to the novel test angles in a

systematic manner that reflected their training experience. Specifically, for participants in group 50, when given a choice between their training angle and a test angle smaller than 50°, they chose the smaller test angle at a higher proportion than they chose their training angle. For participants in group 75, test angles larger than 75° were chosen at a higher proportion compared to the training angle of 75°. However, a closer analysis of the response patterns between the two groups suggests that they were encoded in different ways, with the smaller angle processed in a more absolute fashion than the larger angle.

For group 50, the mean proportion of choices to the two smaller angles nearest to 50° (40° and 45°) was greater than the total proportion of choices made to the two angles furthest away (30° and 35°). However, the proportion of choices directed to each of the four smaller test angles was also greater than the proportion of choices directed to the training angle, meaning that the smallest test angles still retained a measure of control over participants' behaviour, albeit at a reduced rate when compared to the test angles nearest to the training angle of 50°. Taken together, these results are evidence for only a partial peak shift response pattern for group 50. For group 75, choices to each of the four test angles larger than 75° were also greater than the proportion of choices directed to the training angle of 75°; however, the proportion of responses to the two larger test angles nearest to 75° (80° and 85°) did not differ from that of the two test angles furthest away (90° and 95°). Therefore, unlike group 50, the proportion of choices made by group 75 to the extreme test angles in the shifted direction did not differ from the proportion of choices to test angles with more similar amplitude to 75°.

Experiment 2

Results from Experiment 1 showed that adult humans generalized their responding to novel angles based upon the size of their rewarded training angle (S+) in relation to a second non-rewarded angle (S-). Results from Experiment 1 also suggest that the manner in which the encoding of angles occurs is dependent upon the size of the angle being learned. Specifically, the presence of a partial peak shift response pattern for Group 50 but not for Group 75 indicates a trend toward more absolute encoding of smaller angles and a more relative encoding strategy for larger angles.

One goal of Experiment 2 was to determine the pattern of responding that adult humans would show when an even smaller angle was included in the set of training angles. A second goal was to determine what the response pattern would be when a relative strategy was no longer available. In Experiment 2, in addition to 50° and 75°, a third angle (25°) was added so that participants were now presented with a choice between three angles during training instead of two. Just as during Experiment 1, only the angle size associated with each group was reinforced during training. Given the tendency for the participants to generalize responding during Experiment 1 it was expected that participants in groups 25 and 75 (the groups trained with the two outermost angles) would show generalization to the novel angles either smaller (group 25) or larger (group 75) than their training angle. Since participants in Group 50 would be prevented from learning a relative strategy during training (their training angle was smaller than some comparison angles but larger than other comparison angles), it was expected that this group would default to an absolute encoding strategy and therefore not show a preference for novel angles on either side of 50° during testing.

Materials and Methods

Participants

A total of 89 students from the University of Saskatchewan (Age = 21.3 years) participated in exchange either for course credit or monetary payment of $10. Participants were randomly assigned to one of three groups, with group 50 reinforced for choosing the 50° angle during training, group 75 reinforced for choosing the 75° angle during training and group 25 reinforced for choosing the 25° angle during training. A total of 4 men and 1 woman failed to pass training and were replaced by a new participant of the same gender so as to maintain an equal amount of men and women in each group (N = 84; 14 men, 14 women per group).

Training

During training three objects were always present and each object projected one of the following angles: 25°, 50°, or 75° and the object projecting the angle was randomized over the course of training. Just as during Experiment 1, an identical covered tin container was positioned in front of each object (the object herein referred to as "angle"). For participants in Group 25, a coin was always placed inside the container positioned in front of the 25° angle, for group 50 it was inside the container in front of the 50° angle, and for group 75 it was inside the container in front of the 75° angle (the tin container with the coin will be referred to as "the correct container"). The positioning of the different angles was counterbalanced. The procedure for choosing a container was identical to Experiment 1 except now participants had a total of three choices (if needed) to locate the correct container instead of two. Training consisted of 12 trials and participants were considered to have passed training if they chose the correct container

first on the final two trials of the session. Just as during Experiment 1, results from testing were only considered for those participants who successfully passed training.

Testing

The testing phase consisted of a total of 34 trials per session comprised as follows: 6 *baseline trials*, 6 *three-angle control trials*, 6 *two-angle control trials*, and 16 *test trials*. Baseline trials were identical to training trials and included reinforcement which meant that the coin was always present inside the correct container and participants were allowed three choices if necessary. Three-angle control trials were identical to baseline trials except that there was no reinforcement and participants were allowed only one choice, with a choice defined as when the participant approached and pointed to what they believed was the correct container. During two-angle control trials the assigned training angle was paired with one of the other original training angles an equal number of times, with the positioning of the angles (either on the left or right) counterbalanced, and participants making a single choice by approaching and pointing to what they believed was the correct container. Furthermore, although the objects remained the same distance from the start position, they now occupied different locations separate from those used during the three-angle control trials (Test position A and Test position B, see *Figure 3-4*). Test trials were identical to two-angle control trials except that the assigned training angle was paired with a novel angle (only two angles were present). There were 16 novel angles in total that ranged in 5° increments from a low of 5° to the highest of 95°. Participants experienced the novel test angles in random order with each test angle used only once over the course of testing. Baseline trials and two and three-angle control trials were interspersed pseudo-randomly between test trials with the condition that no trial of the same type was conducted on consecutive trials.
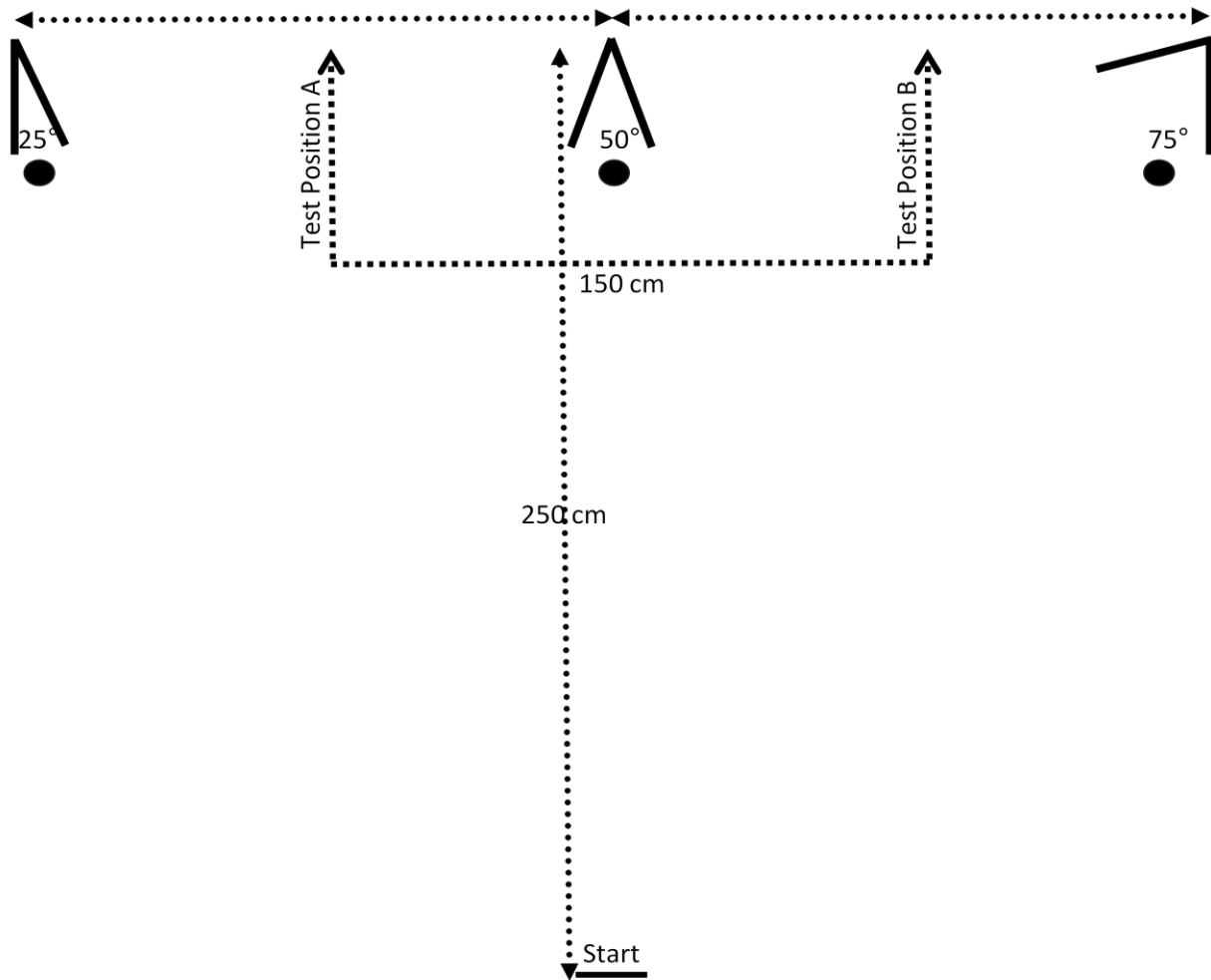
Figure 3-4: A schematic top-down representation of the positions of the three objects during training in Experiment 2. The training angles were 25°, 50°, and 75°. Note that the positioning of the different angles was counterbalanced. The dark circles represent the identical covered tin containers that were positioned in front of each angle. A trial always began with the participant approaching the angles from the start position. During testing only two angles were present, one of which was always the assigned training angle, with one angle located at Test position A and the second located at Test Position B.

Results Experiment 2

Control Test Accuracy. Control trials were identical to training trials except they were non-reinforced. To examine whether participants continued to respond accurately to S+ across control trials a separate Friedman's analysis was conducted for each group. The results of the test showed no significant difference for two or three-angle control accuracy across trials for group 25 ($M = .99$, $SEM = .006$); group 50 ($M = .99$, $SEM = .006$); or group 75 ($M = .99$, $SEM = .006$), $X^2(5) = 5.00$ for each group, $ps = .419$. To determine whether the pooled data for the two and three-angle control accuracy was maintained throughout testing separate binomial tests were conducted for each group. Results showed that choice accuracy was near ceiling across groups: group 25 ($M = .96$, $SEM = .006$); group 50 ($M = .96$, $SEM = .006$); or group 75 ($M = .96$, $SEM = .006$), $ps < .001$, binomial tests. These results show that response accuracy remained near ceiling during control trials for all groups throughout testing.

Area Shift Analyses. In order to determine the presence of an area shift to test angles above or below the training angle, separate Wilcoxon signed ranks tests were conducted each for groups 25, 50, and 75 comparing the mean proportion of choices to the four angles immediately above S+ with the mean proportion of choices to the four angles immediately below S+.

For group 25 the mean proportion of responses was greater ($M = .46$, $SEM = .080$) for the four angles below 25° (5°, 10°, 15°, and 20°) compared to the four angles ($M = .13$, $SEM = .035$) immediately above 25° (30°, 35°, 40°, and 45°), $z = 2.72$, $p = .007$, resulting in a response bias for angles smaller than the training angle of 25°.

For group 50 there was no significant difference between the mean proportion of choices ($M = .16$, $SEM = .043$) immediately below 50° (30°, 35°, 40°, and 45°) compared the four angles

(M = .14, SEM = .033) immediately above 50° (55°, 60°, 65°, and 70°), z = .136, p = .892, resulting in a lack of response bias on either side of the training angle of 50°.

For group 75° the mean proportion of choices was greater (M = .78, SEM = .058) for the four angles above 75° (80°, 85°, 90°, and 95°) compared to the four angles (M = .13, SEM = .033) immediately below 75° (55°, 60°, 65°, and 70°), z = 4.29, p < .001, thus showing a bias for toward angles larger than the training angle of 75°.

Peak Shift Analyses. Just as during Experiment 1, in order for a response pattern to be considered a peak shift two conditions had to be met: 1) a higher rate of responding to the two test values nearest S+ in the shifted direction (S+Near) over S+, and 2) a decrease in the proportion of responses between the two test values nearest S+ (S+Near) compared to the two extreme test angles in the shifted direction (S+Far). Since there was no significant response bias to test angles on either side of the training angle, no further peak shift analyses were conducted on group 50.

Group 25. Separate binomial tests were conducted for each of the four tests values smaller than 25° to determine whether the proportion of responses to that particular angle exceeded chance responding (.50). Neither of the mean proportion of choices to each of the two angles associated with S+Near (15°: M = .46, SEM = .096; 20°: M = .57, SEM = .095) exceeded what would be expected by chance, (p = .851 and p = .572 respectively, binomial tests); similarly, the mean proportion of choices to each of the two angles associated with S+Far (5°: M = .36, SEM = .092; 10°: M = .43, SEM = .095) also did not exceed what would be expected by chance, (p = .185 and p = .572 respectively, binomial tests).

In order to determine whether the two test angles comprising either S+Near or S+Far showed similar rates of responding and thus could be grouped, separate Wilcoxon signed ranked tests were conducted for each pair, with results showing that the proportion of choices was not significantly different in either case (S+Near: $z = 1.13$, $p = .257$; S+Far: $z = 1.00$, $p = .317$). A subsequent Wilcoxon signed ranks test comparing the mean proportion of choices to S+Near ($M = .52$, $SEM = .083$) with that of S+Far ($M = .39$, $SEM = .087$) was significant, $z = 2.11$, $p = .035$, revealing a higher mean proportion of choices to the two test angles nearest 25° compared to the two test angles furthest away (see *Figure 3-5*).
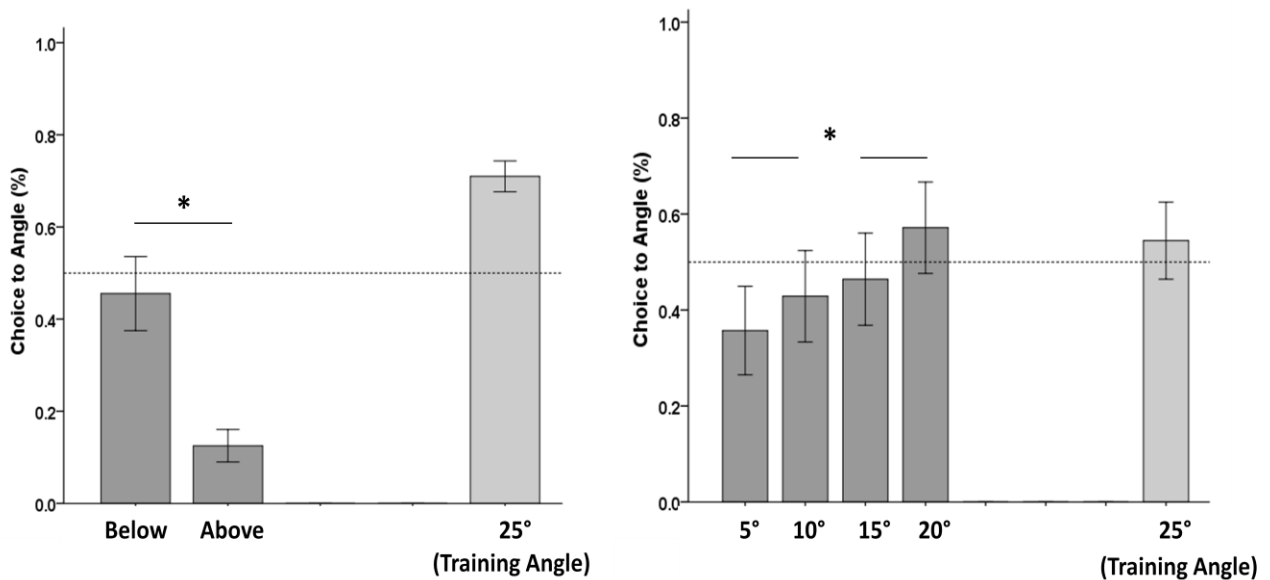
Figure 3-5*: The left most figure shows the area shift for group 25 in Experiment 2 with the mean proportion of choices to the four test angles below 25° (S+) significantly greater than the mean proportion of choices to the test angles immediately above 25°. The lighter bar to the right shows the mean proportion of responses to 25° when pitted directly against the test angles indicated. The rightmost figure shows that the mean proportion of choices was not greater than chance for any of the four smallest test angles when individually pitted against 25°. The mean proportion of choices to the two test angles comprising S+Near was significantly higher than the mean proportion of choices to the two test angles comprising S+Far. The lighter bar to the right represents the mean proportion of choices to 25° when directly pitted against each of the angles indicated. Overall the results show an area shift for group 25 with mean responding to the two smallest test angles significantly reduced compared to the next two smallest test angles. *Significant at $p < .05$.

Group 75. The mean proportion of choices to each of the two S+Near test angles (80°: M = .64, SEM = .092; 85°: M = .89, SEM = .062) was significantly greater than what would be expected by chance for the 85° test angle ($p < .001$) but not the 80° test angle ($p = .185$, both binomial tests). Mean choices to each of the two S+Far test angles (90°: M = .75, SEM = .083; 95°: M = .82, SEM = .074) both exceeded what would be expected by chance, ($p = .013$ and $p =$ .001 respectively, binomial tests).

In order to determine whether the two test angles comprising either S+Near or S+Far showed similar rates of responding and thus could be grouped, separate Wilcoxon signed ranked tests were conducted for each pair and results showed a significant difference between the two S+Near test angles but not the two S+Far test angles (S+Near: $z = 2.11$, $p = .035$; S+Far: $z =$ 1.41, $p = .157$). Since the proportion of choices to the two S+Near test angles was significantly different, the combined S+Near and S+Far test angles were not directly compared. However, a Wilcoxon signed ranks test instead comparing the proportion of choices to the largest S+Near test angle (85°) with the proportion of choices to the largest S+Far test angle (95°) was not significantly different, $z = 1.41$, $p = .157$, which is not consistent with a peak shift (see *Figure 3-6*).
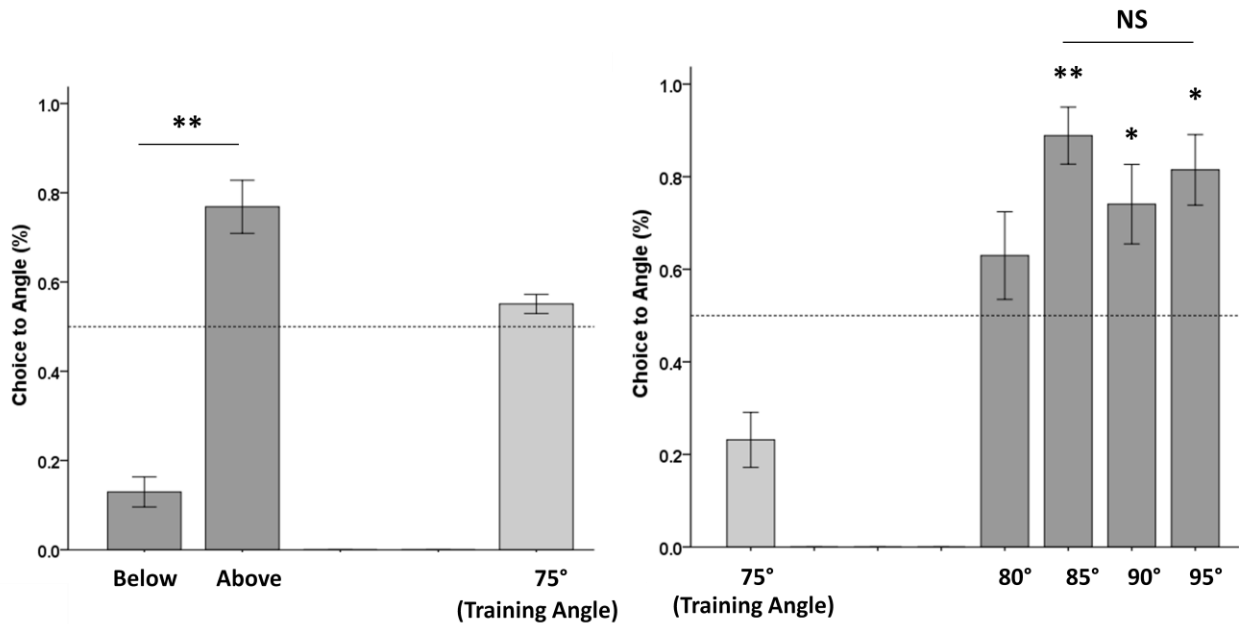
Figure 3-6*: The leftmost figure shows the area shift for group 75 in Experiment 2 with the mean proportion of choices to the four test angles above 75° (S+) significantly greater than the mean proportion of choices to the four test angles immediately below 75°. The lighter bar to the right represents the mean proportion of choices to 75° when directly pitted against the test angles indicated. The rightmost figure shows that the proportion of choices was significantly greater than chance for each of the four largest test angles except 80° when individually pitted against 75°. The difference in the mean proportion of choices to the 85° test angle and 95° test angle however was not significant. The lighter bar to the left represents the mean proportion of choices to 75° when pitted directly against each of the angles indicated. Together these results are supportive of an area shift only for group 75 in Experiment 2. *Significant at $p < .05$, **Significant at $p < .001$.

Discussion Experiment 2

Results for group 75 from the current experiment were consistent with group 75 from Experiment 1 whereby participants generalized their responses to include test angles larger than the training angle of 75°. However, unlike group 75 from Experiment 1, the participants in group 75 in the current experiment did not choose the immediately larger angle (80°) closest to the training angle at a rate greater than what would be expected by chance. The fact that

participants in group 75 during Experiment 2 did not display a similar finding to that of Experiment 1 may be the result of the procedural difference of learning to discriminate their training angle from two other angles during training instead of just one. However, the proportion of choices made by the current group 75 to the second test angle (85°) immediately larger than 75° was significantly greater than what would be expected by chance. Just as during Experiment 1, the proportion of choices directed to the very largest test angle (95°) also exceeded chance responding. Furthermore, the proportion of responses between these two test angles – one closer in amplitude to the training angle and one furthest away – was not significantly different, indicating that participants were undeterred from selecting even the very largest test angle.

The participants from group 50 during Experiment 2 differed from those during Experiment 1 in that they were not provided with a straightforward strategy to encode the training angle in relative terms during discrimination training along with the other two angles. This was due to the fact that during training the 50° angle was neither the smallest nor the largest of the three training angles, thus reducing the likelihood of it being encoded in relative terms and thereby encouraging a more absolute strategy to be adopted. In fact this was the case, with participants not showing a preference for test angles either side of 50°, indicating a lack of an area shift above or below the training angle of 50°.

For group 25, individuals chose test angles smaller than 25° more than they chose test angles that were larger, with the mean proportion of choices to the four test angles smaller than 25° greater than the mean proportion of choices to the four test angles immediately larger. However, there was a limit to which participants chose smaller angles as evidenced by the finding that the mean proportion of choices to each test angle smaller than 25° never exceeded chance responding. However, the mean proportion of choices to the two smaller test angles

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closest to 25° (15° and 20°) was greater than the mean proportion of choices to the two smallest test angles (5° and 10°), showing that participants were less inclined to choose test angles at the extreme end of the test range.

<center>General Discussion</center>

Adult humans were trained and tested on their ability to discriminate geometric angles during a real-world task. During Experiment 1, they were presented with two angles (50° and 75°) and trained to choose one of them over the other, with group 50 trained to choose the 50° angle and group 75 trained to choose the 75° angle. During testing each group was given a choice between its training angle (S+) and one of a series of novel test angles that was either smaller or larger than S+. Results from Experiment 1 showed that people systematically generalized their responses during testing, with group 50 choosing angles immediately smaller than S+ at a higher proportion than they chose angles that were immediately larger; group 75 showed a similar response pattern but in the opposite direction with a higher proportion of choices to angles larger than S+ in comparison to angles that were immediately smaller. However, the response pattern of group 50 to the test angles smaller than 50° also revealed a partial peak shift effect, with angles closer to 50° chosen at a higher proportion compared to angles further away. Group 75, however, showed no such effect for test angles that were larger than 75° with all of these angles chosen at equally high rates regardless of how large they became. Together these findings show that people tended toward a more absolute strategy when trained on the smaller angle compared to when they were trained on the larger angle. This pattern was extended during Experiment 2 whereby discrimination learning was conducted with

<center>66</center>

three angles but testing occurred with just two, one being a novel test angle and the other being the training angle. Interestingly, participants in the group trained to respond to the smallest angle (25°) did not choose any of the test angles smaller than 25° at a higher rate than they chose the training angle, suggesting that the smaller the training angle became the less susceptible it was to generalization to even smaller test values.

Results for group 50 from Experiment 1 showed that the response pattern was only partially peak shifted. Specifically, although the mean proportion of choices directed to each of the test angles smaller than 50° exceeded choices to S+, there was still a significant decrease between the proportion of choices to the two test angles nearest 50° and the two test angles furthest away. It should be noted that peak shift is not as typical in human research as it is in non-human animal research, especially when the stimuli is simple and varies only along a single dimension (Willis & McIntosh 1998), as was the case here. This species difference is illustrative of the fact that when a relative rule can be applied and used to discriminate one exemplar from another within a given category humans are strongly driven to use such a rule (Livesey & McLaren 2009). In instances where peak shift has been demonstrated in humans (e.g., faces: Spetch et al., 2004 or spatial position: Cheng & Spetch 2002), the stimuli did not lend itself to easy categorization and therefore was likely more resistant to relative rule learning. Indeed, peak shifted generalization gradients have shown themselves to be sensitive to other basic manipulations such as the adjustment of differences between S+ and S- (Cheng et al., 1997) or the biasing of the range of test values by including more or less test values on either side of S+ (Thomas, 1993).

During Experiment 1 the mean proportion of choices directed by group 75 to each of the test angles larger than 75° exceeded chance responding. However, unlike group 50, individuals

in group 75 were equally as likely to choose the two larger test angles closest to 75° (80° and 85°) as they were to choose larger test angles furthest away (90° and 95°). These findings suggest that during training individuals in group 75 learned to discriminate the correct angle based on its size relative to the second angle (i.e., that it was simply larger than the opposing angle of 50°). During testing participants appear to have extended this association to all angles larger than 75° by choosing these larger angles consistently at a rate greater than chance. Overall, the pattern of results for Experiment 1 suggest a tendency for absolute learning of the smaller training angle compared to relative learning of the larger training angle.

Results for group 75 during Experiment 2 were very similar to the results from group 75 during Experiment 1 with the sole exception being the lack of significant proportion of choices to the 80° test angle, which was the nearest test angle larger than 75°. It is not clear why men and women chose this angle at a significantly higher proportion than would be expected by chance during Experiment 1 but failed to do so during Experiment 2. One possibility is that the procedural difference between discriminating three angles instead of just two during training may have altered the sensitivity of participants in this group when making this fine angle judgement, at least for the larger angles. Beyond this exception, however, participants chose each of the remaining large test angles at higher proportion than they chose the training angle, just as group 75 had during Experiment 1. Overall, results for the participants in each of the respective groups trained with the 75° angle during both experiments show a strong pattern of relative rule learning for the largest geometric angle.

It is interesting that an absolute encoding pattern was found for group 50 during Experiment 2 when the training procedure did not allow for a clear relative rule with which individuals could discriminate their angle from the other two. Specifically, peak responding

remained at the training angle of 50° and there was no significant shift to test angles immediately above or below this value. This result highlights the fact that the ability of people to discriminate geometric angles can be remarkably accurate when an explicit relative option is not made available to them. This is important to note since it shows that the tendency for people to generalize their responses in a manner consistent with the size of their training angle is not due to a lack of ability to accurately discriminate geometric angles. However, whether discrimination accuracy remains the same for all sizes of angles – acute as well as obtuse – is yet to be determined, as it may be that acute angles may generally be easier to discriminate than obtuse angles. If larger angles do indeed lend themselves to be encoded and learned in more relative terms, as appears to be the case, it might then be expected that the discrimination might be made more challenging if this middle angle (in a three angle discrimination) was of a larger amplitude.

For participants trained on the smallest angle (group 25) during Experiment 2 none of the mean proportional choices to test angles below this value exceeded chance, a result that contrasts with findings for the smallest angle (50°) during Experiment 1. This discrepancy between the respective response patterns of the smallest angles in both Experiments 1 and 2 reveals a graded decline in generalized responses to test angles as they became smaller. In both instances there was still a reduction in responding to the very smallest angles of the test range compared to those angles nearer S+. However, for group 50 during Experiment 1, mean responding still exceeded chance for all test angles below the training angle whereas for group 25 during Experiment 2 this was not true for any of the test angles below 25°. Overall, the findings from both experiments point to a consistent pattern in that the smaller the training angle became the more distinctive properties it appears to have taken on and consequently the more resistant it may have been to broader generalization.

The finding that smaller and larger geometric angles may be processed differently has been found previously in reorientation experiments. Tommasi and Polli (2004) trained chicks to locate food hidden near one corner of a parallelogram-shaped enclosure whereby one set of diagonally opposite corners projected a 60° angle and the other pair of diagonally opposite corners projected a 120° angle. The chicks could learn to associate the location of the hidden food reward with the angle of the nearby corner, or alternatively they could use the differential length of the adjoining walls that formed the corner (i.e., one wall comparatively shorter than the other). Testing with novel shaped environments in which the corner angle cues and wall cues were presented in isolation demonstrated that the chicks could use either the corner angles or wall lengths to make the correct choice. However, during a cue conflict test in which chicks could choose either corner angles or wall lengths as their preferred cue, an interesting finding appeared: for chicks trained to approach corners projecting larger angles, it was the length of the adjoining walls that was the stronger cue but for chicks trained to approach corners projecting the smaller angle it was the corner angle that was weighted more heavily, suggesting that for chicks smaller angles were more salient than larger angles. Although, an alternative strategy offered by the researchers, but thus far untested, is the possibility that the chicks' choices were instead guided by changes based on a threshold generalization gradient. Specifically, during conflict testing, chicks that had been trained to approach the smaller corner angle may have avoided the corners with the larger angle (but with the correct wall lengths) since this angle was double the size of the training angle and thus represented a more severe change than the reduction in angle size confronting chicks trained to approach the larger corner angles.

In related research with adult humans, Reichert and Kelly (2010) used an object array to study the use of local and global geometry in a real-world task. Four wooden objects were

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arrayed such that each object occupied one point of a four-point rectangular configuration. Each object was constructed of two identical pieces of wood joined by a hinge that allowed the objects to expand or contract to form various geometric angles. Two diagonally opposite objects each projected a 50° angle and the other two diagonally opposite objects each projected a 75° angle. Men and women were trained to find a reward (a coin) hidden near an objecting either projecting a 50° angle (group 50) or a 75° angle (group 75), thus allowing them to use these local angle cues to reliably locate the reward (alternatively, they could also use the rectangular shape of the array to accomplish the task). During testing when the shape of the array was converted to a square, thus negating the global shape cue but preserving the local angles of the objects, participants in group 50 were able to use the angles to choose correctly whereas participants in group 75 were not. Once again, these findings illustrate that smaller angles appear to hold a greater degree of salience as reorientation cues in comparison to larger angles.

Why might objects that project smaller angles provide more salient spatial cues than larger angles? One possibility is that, as the distance between the wooden edges forming the angles is shortened, the ability to judge the angle size becomes more precise and consequently the angle takes on more distinctive qualities – indeed, qualities more akin to featural cues than to geometric cues. If this is the case, then within the context of a reorientation task, it might be expected that smaller angles would hold more salience than larger angles and therefore would be more useful to an organism because they are more featurally distinct. Conversely, within the context of a discrimination task, this distinctiveness would also allow a smaller angle to be more resistant to broader generalization to increasingly smaller angles since this type of responding would violate its perceived uniqueness. An interesting extension of this research would be to examine this pattern of results with obtuse training angles only, as opposed to the acute angles

studied here, to determine whether this pattern of results is truly a function of angle size only or if relative comparisons during training might also play a role.

The implications of the current research suggest that certain geometric properties are learned and processed differently than others. The fact that smaller angles were less susceptible to broader generalization than their larger counterparts speaks to the possibility that smaller angles may be perceived as being more distinct than larger angles. In order to investigate this possibility further it would be useful to conduct similar angle discrimination experiments with non-human animal species. Given that non-human animals are less likely than humans to follow a relative rule-based strategy during discrimination tasks (Willis & McIntosh, 1998) as well as spatial search tasks (Spetch et al., 1997; MacDonald et al., 2004), it would be interesting to see whether they too show a tendency toward relative encoding of larger angles compared to smaller angles. Of particular interest would be comparisons between animals in which behavioural differences in geometric learning have already been well established. An example of such a comparison would be that between food-storing and non food-storing birds whereby food-storing birds have shown a higher degree of reliance upon geometric spatial cues as compared to non-storing birds (Clayton & Krebs, 1994). Might these species differences also lead to differences in the encoding of geometric angles? Such a comparison could yield valuable clues as to the potential learning flexibility that may be elicited by different sizes of geometric angles.

CHAPTER FOUR

Use of local and global geometry from object arrays by adult humans

Introduction

In order to successfully navigate from one locale to another it is necessary for an

organism to maintain a correct sense of heading in relation to its surroundings, an ability known

as orienting. However, if an animal loses its sense of heading, there are two general types of

visual-based environmental cues that an organism can use to reorient: featural and geometric

cues. Featural cues include distinctive information such as the pattern, texture, and/or color of

objects or surfaces within an environment, whereas geometric cues include information such as

distance and direction between objects or surfaces. A prominent geometric cue inherent within

enclosed environments is the overall shape of the space as defined by both the lengths of

individual walls and the angular information provided by corners. Early research showed that

disoriented rats relied more on the shape of a rectangular enclosure to reorient compared to the

seemingly more salient features (Cheng, 1986). In the reference memory experiment of Cheng's

study, featurally distinctive panels were placed at each corner of a rectangular enclosure and rats

were trained to search for appetitive reinforcement which was only available at one corner. Once

the rats learned to limit their searching to the reinforced corner, several transformation tests were

administered. During one of these tests (the affine transformation), each panel was moved by

one corner, thereby placing it in a corner geometrically different from the corner it had occupied

during training. The rats made few choices to the corner with the correct feature and instead searched primarily at the two corners that maintained the correct geometry from training. As diagonally opposite corners of a rectangle are geometrically indistinguishable, the rats divided their choices between the correct corner and its geometric equivalent; the rats made *systematic rotational errors.*

In the years following Cheng's study, the rectangular enclosure paradigm has been used with a variety of animals [e.g., pigeons (Kelly, Spetch, & Heth, 1998), chicks (Vallortigara, Zanforlin, & Pasti, 1990), fish (Sovrano, Bisazza, & Vallortigara, 2002), rhesus monkeys (Gouteux, Thinus-Blanc, & Vauclair, 2001), ants (Wystrach & Beugnon, 2009), as well as human children (Hermer & Spelke, 1994), and human adults (Kelly & Bischof, 2005; 2008; Ratcliffe & Newcombe, 2008) – for a review see Cheng & Newcome, 2005] and this research has shown that although many species use distinctive featural information, the encoding of geometry is robust across a wide range of species with profoundly different ecologies.

Although walled enclosures continue to be invaluable for research investigating cue use for orientation, understanding how human and non-human animals encode geometric information from object arrays offers insight into how geometry might be used in less structured environments. A typical orientation task using an object array consists of a set of objects placed such that the overall configuration forms a perceptible geometric shape (e.g., four landmarks placed to form a rectangle) with an organism required to use this configuration to reliably search for a hidden goal. Unlike research conducted within similarly-shaped walled structures, several species have been shown to rely on local cues over the global structure of a landmark array [e.g., pigeons (Spetch et al., 1997), marmoset monkeys and children, (MacDonald, Spetch, Kelly, & Cheng, 2004)].

However, research with humans has showed that young children may not encode the geometry of a landmark array even though they show primary encoding of geometry from a walled enclosure. Gouteux and Spelke (2001) trained toddlers to search for a toy hidden in one of four identical boxes arranged in the shape of a rectangle. After watching an experimenter hide the toy in one of the boxes, the child was then slowly spun in place with his/her eyes closed until disoriented. With eyes open the child was asked to indicate which box contained the toy. Results showed that the children did not search in the correct box or its rotational equivalent above chance level, indicating that they had not encoded the rectangular shape of the array. Yet, in a subsequent experiment, Gouteux and Spelke (2001) found that similarly-aged children trained with the same array could search in the geometrically correct boxes when truncated walls were placed between the objects. That the children did not search correctly in the first task appears to be related to their inability to configure the objects within the array as a collective shape and instead viewed each box independently. These findings are supportive of the theory of adaptive combination (Cheng & Newcombe, 2005; Twyman, Friedman, & Spetch, 2007; Ratliffe & Newcombe, 2008), whereby geometric and landmark information operate in tandem for control of search behaviour, with the relative weight placed on either type of cue dependent upon the reliability, validity, and saliency of the information. Within this context, shape information presented in the form of an array of landmarks may be seen as less salient or reliable than when it is provided by a similarly-shaped walled structure. In contrast to children, adult humans show evidence that they perceive an array of identical objects in configural form. When tested with the same rectangular array of four identical boxes as the children, Gouteux and Spelke (2001) found that adult participants directed the majority of their choices to either of the two geometrically correct boxes.

Although these studies provide information as to how human and non-human animals use global geometric cues for reorientation, less is known about the use of local geometric cues. Tommasi and Polli (2004) tested chicks in an enclosure that was constructed in the shape of a parallelogram. Individual corners within this space could, as in a rectangle, be distinguished by the relative lengths of their adjoining walls. However, in a parallelogram-shaped structure, individual corners can also be distinguished by the angles subtended by the adjoining walls, therefore providing both global geometric information (shape as defined by relative lengths of walls) and local geometric information (the angle formed by a corner). The chicks were divided into two groups, with one group trained to search for food at corners projecting an acute angle (60°) and another group trained to find food at corners projecting an obtuse angle (120°). Transformation tests were conducted to examine whether the chicks had encoded the local (i.e., angles) and global (i.e., wall lengths) cues of the training environment. Testing conducted in a rhombus-shaped environment with equilateral walls preserving the different angles at each corner revealed that chicks could reliably use the local geometric information to orient. Further testing in a rectangular-shaped enclosure in which all corner angles were equal showed that the chicks could also use relative wall length as an orientation cue.

An interesting result occurred when the chicks were tested with the local and global cues providing conflicting information as to the goal location (the environment was modified to form a mirror-image parallelogram). When chicks were required to choose between the relative lengths of the walls and the angle subtended by those walls, the two groups of chicks responded differently, suggesting that the training angles differentially influenced search behavior. Specifically, chicks that had been trained to search at corners projecting acute angles continued to choose the corners that maintained those angles even though the relative lengths of the

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adjoining walls were now opposite from what they had been during training. In contrast, chicks trained to search at corners projecting obtuse angles chose corners that preserved the correct length of walls from training, even though these corners now projected smaller angles.

Using a similar approach, Hupbach and Nadel (2005) trained human children to search for an object they had previously seen being hidden in one corner of a rhombic-shaped environment. In this type of environment all the walls are of equal length, effectively negating global geometry as a viable cue, leaving the local corner angles as the only useable information as to the location of the hidden object. One set of diagonally opposite corners projected identical acute angles and the other set of corners projected identical obtuse angles. Following disorientation, the children were asked to identify the corner in which the object was hidden. The researchers found that the children could successfully use the angular information at the corners to distinguish the two geometrically correct corners from the two geometrically incorrect corners. However, this ability was age-dependent, with children under four years of age unable to use these local angle cues. Previous research has shown that children less than two years of age are able to use the relative length of walls to reorient within a rectangular space (Hermer & Spelke, 1994).

A problem with examining the use of local and global geometric cues in the manner discussed in the aforementioned experiments is that it is difficult to dissociate the influence of the geometric information coming from the angular cues (i.e., the corners) and the surface cues coming from the walls. That is, the local geometry provided by the corner angles is embedded within the global shape of the space through the presence and continuity of walls. Our current experiment was designed to separate this local angle information from the global shape of the space through the use of an object array. Four discrete objects were arranged in the shape of a

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rectangle, with each object constructed such that it projected an angle toward the center of the array, just as would normally be encountered by a corner subtended by two walls within an enclosed space. During training, participants were rewarded for searching at one of the objects that projected a specific angle. Participants were subsequently tested on their ability to use this local angle information to reorient when the shape of the array was no longer informative, or to use the global shape of the array when the local angular information was no longer informative. A Cue Conflict test was also conducted to examine whether the local and global geometric cues were weighed differently by participants when the two were placed in direct competition. A further goal of the experiment was to examine any specific differences between men and women in their encoding of local and global geometry in this task.

Materials and Methods

Participants

A total of one hundred and fifteen first-year university students from the University of Saskatchewan (44 men, 71 women) participated in this study in exchange for course credit. Data were used only for participants who successfully completed training and advanced to testing (30 men, 30 women).

Apparatus

A four object rectangular array (300 cm x 150 cm) was set up within a larger experimental room (570 cm long x 275 cm wide x 270 cm high) with walls enclosed by opaque white curtains which were identical. The floor was covered in shredded paper to remove any

extraneous visual cues. Each object within the array consisted of two uniformly identical pieces of wood (each piece of wood was 30 cm wide x 1.5 cm deep x 60 cm high) joined together with a hinge so that the pieces could expand or contract to form an angle. A blue colored stripe (4 cm wide) was located along the top edge of each wooden piece, and a second blue stripe was located 26 cm below the first. Furthermore, two red colored stripes (2 cm wide) were located, one 4 cm from the top edge and a second 36 cm from the top edge of each wooden piece. Each colored stripe spanned the entire width of the wooden pieces. During training the top left object (as viewed from the center of the array) was always set at 50° and the top right object was always set at 75°. Diagonally opposite objects always projected the same angle (see *Figure 4-1A*). Four tin containers (8.5 cm diameter) covered by identical brown plastic lids were placed in front of the objects, with one tin in front of each object.

General Procedure

All training and testing was conducted individually. Participants were verbally instructed as to the task requirements in a waiting area separate from the experimental room. They were told that they would be searching for a coin hidden inside one of several containers located in another room. They were not provided with any information regarding featural or geometric cues. Participants were asked to wear earplugs to mask any external auditory cues. They were then blindfolded by a second researcher and led by that researcher into the experimental room. Once inside the experimental room they were led to a swivel chair and asked to have a seat; the individual was rotated slowly by the researcher for 45 s at a rate of approximately 12 rpm. The direction of rotation was periodically reversed while the researcher walked in circles so as to not serve as an orienting cue. Following rotation, the researcher randomly walked the participant

around the room while a second researcher removed the chair. The participant was stopped at a random point outside the array and the blindfold was removed.

Following removal of the blindfold the participant was asked to search for the hidden coin by picking up a container and shaking it to determine if the coin was present. If the participant was unable to locate the correct container within two choices, one of the researchers indicated the correct container to the participant. Following each trial the participant was blindfolded once again and led into the waiting room where s/he remained until the start of the next trial. Between trials the array was repositioned to correspond to one of eight different orientations, within the larger experimental room, separated by 45° (i.e., 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315°) such that a correct location was never in the same absolute position within the room from one trial to the next. Each participant experienced all eight rotations over the course of training.

Training

Participants were divided into two groups based on their training angle and its corresponding rewarded container. Since diagonally opposite objects within the array projected identical angles their associated containers were both considered to be correct (herein referred to as the "correct containers"). For members of group 50° the correct container was located at one of the objects projecting a 50° angle and for group 75° the correct container was located at one of the objects projecting a 75° angle. A single session, consisting of eight training trials, was conducted. Only participants who made two consecutive correct first choices during the last two trials (i.e., trials seven and eight) advanced to testing. Participants who did not reach criterion were thanked for their participation and did not proceed to testing. In order to maintain an equal

number of men and women in each group, for each participant who failed to advance to testing another participant of the same gender was recruited, until an equal number of men and women (15 men and 15 women each of group 50° and group 75°) had successfully completed training.

Testing

All participants who met the training criterion were given three consecutive test trials. During testing, participants were told they were still required to make two choices to locate the coin, but if the coin was not found they would no longer be shown the correct location. Unlike training trials, the test trials were non-reinforced (i.e., no coin was present). The order of the three testing conditions was counterbalanced across participants.

Global Cues Test. This test condition examined whether the participants could use only the global shape of the array to locate the correct container in the absence of local angle cues. Thus, during this test condition the configuration of the array retained the rectangular shape, but all objects projected an identical novel angle (90°) not used during training (see *Figure 4-1B*).

Local Cues Test. This test condition examined whether participants could use the local cues from the angles to reorient when the shape of the array was transformed into a square shape and thus did not provide any informative geometric information. The objects of the array maintained the same angles as they had during training (see Figure *4-1C*).

Cue Conflict Test. This test condition examined whether participants chose to use the local angles of the objects or the global shape of the array when the two types of cues provided conflicting information as to the location of the correct container. During this test condition, the configuration of the array remained rectangular but each object was moved one position

clockwise. This affine transformation essentially manipulated the array such that the two objects

with 50° angles were switched with the two objects with 75° angles (see *Figure 4-1D*).

A)

Training

B)   C)   D)

Global Cues Test   Local Cues Test   Cue Conflict Test
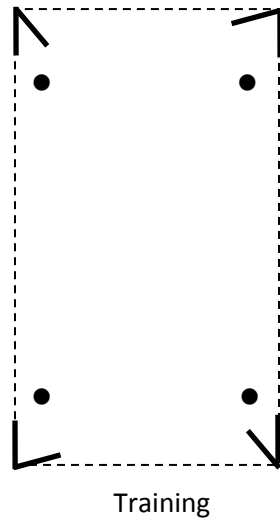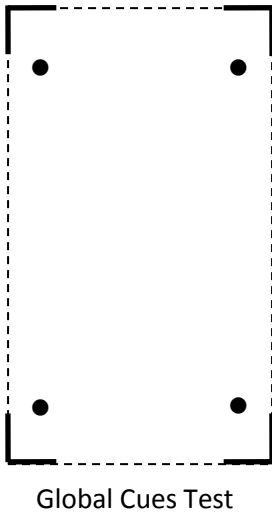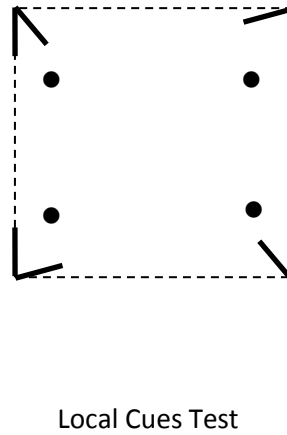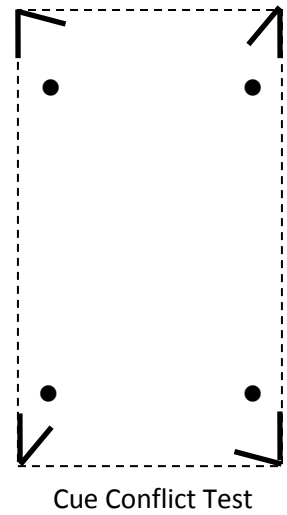
Figure 4-1. A) A schematic representation of the configuration of the objects during training. Two angles with differing degrees were used (i.e., 50° and 75°). Diagonally opposite objects projected the same angle. In front of each object was a covered container (as represented by the filled circular symbols). The hashed lines are present only to illustrate the rectangular shape of the array. B) The configuration of the objects during the Global Cues test. All of the angles of the objects are set to 90° during this test. C) The configuration of the objects during the Local Cues test. The angles of the objects remained the same as during training but the shape of the array was converted into a square. D) The configuration of the objects during the Cue Conflict test. The shape of the configuration remained as a rectangle but the original training angles switched positions within the array.

Results

All data were re-scored by a second researcher naïve to the hypotheses of the study; reliability was 100%. A total of 14 men and 41 women did not meet the training criterion and therefore did not advance to testing; this sex difference was significant ($z = 4.91$, $p < .001$, independent proportions z-test).

The number of first choices made to a correct container was calculated for all participants. For each test, participants received a score of 1.0 for directing their first choice to either of the two correct containers and 0 for choosing either of the two incorrect containers. Separate binomial tests were conducted for Group (group 50° and group 75°) and Gender (men and women) on each of the three tests. Finally, we examined whether choice accuracy between men and women was affected by the size of their correct training angle. To analyze this we conducted separate independent proportions z-tests for group 50° and group 75° comparing the proportion of correct choices men and women made during each test. A p value criterion of .05 was used for all statistical analyses and chance responding was .50 for all tests. For the Global Cues and Local Cues tests, one-tailed tests were used because our apriori hypothesis was that participants would make more correct choices compared to chance (a directional hypothesis). However, the significance of these tests (and thus our conclusions) do not change if two-tailed tests were to be used. For the Cue Conflict test, we did not have a directional hypothesis so two-tailed tests were conducted.

Global Cues Test. Overall, neither men nor women were able to use global geometry alone to search for the correct container, regardless of the size of their initial training angle. During this test all the objects were set to a novel angle of 90°, thus making all the local

geometric cues identical and therefore, uninformative. A choice was considered correct if it was directed to a container positioned in front of an object located in the same global geometric position within the array that the training angle had occupied during training.

For the variable of Group, neither participants in group 50° (M = .60, SEM = .091) nor group 75° (M = .60, SEM = .091) chose a correct container at a rate greater than would be expected by chance [(p > .05, one-tail binomial tests) see Figure *4-2A*].

For the variable of Gender, neither men (M = .63, SEM = .089) nor women (M = .57, SEM = .092) chose a correct container at a rate greater than would be expected by chance [(p > .05, one-tail binomial tests) see Figure *4-2B*]. Separate independent proportions z-tests revealed no significant differences in the proportion of correct choices made by men and women in group 50° or group 75° (p > .05).

A)
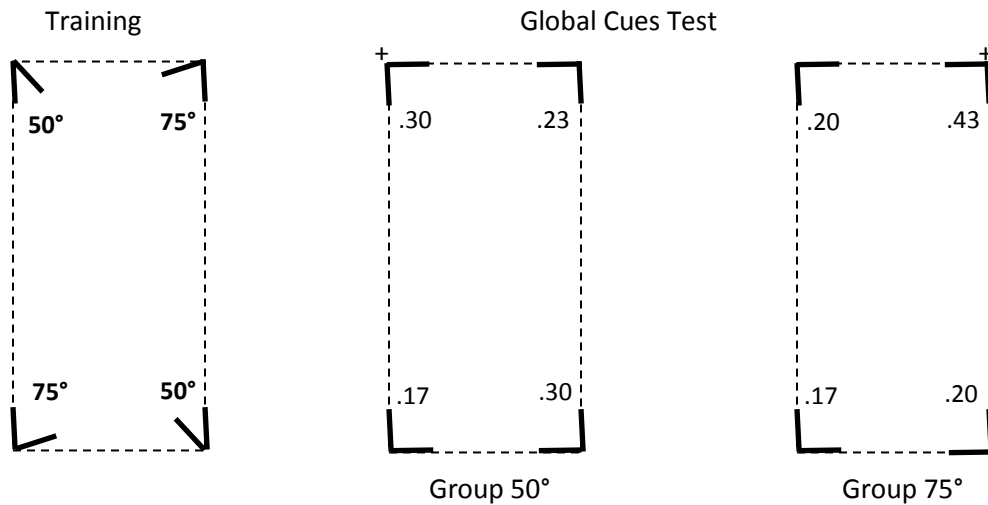
B)
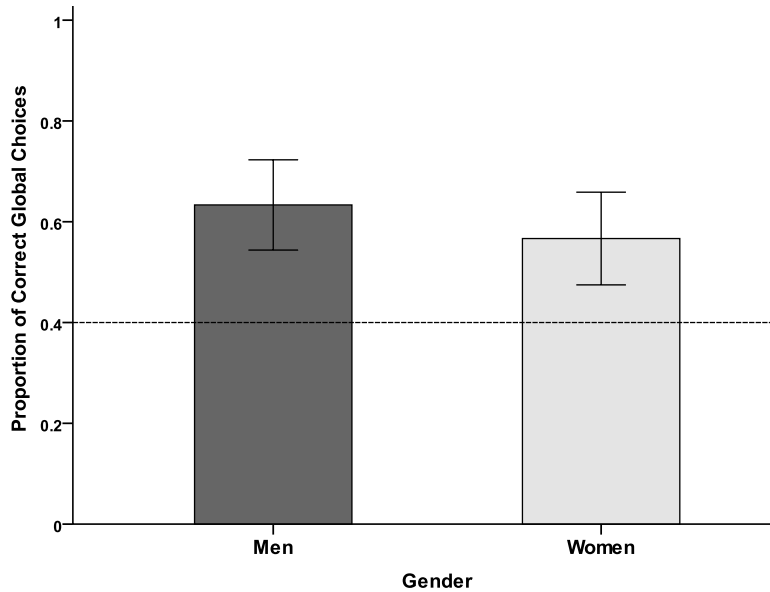
Figure 4-2. A) The leftmost schematic depicts the training setup indicating which objects projected 50° or 75° angles. The middle and rightmost schematics show the distribution of choices for the Global Cues test based on training group. During testing all the angles were set a novel angle of 90°. For illustrative purposes the test figures depict either the top left object (for Group 50°) or the top right object (for Group 75°) as the object associated with the correct container (+), although this was counterbalanced during the experiment. B) Results for the main effect of Gender for the Global Cues test. Chance is indicated by the hashed line at 0.50.

Local Cues Test. The men were able to accurately use the local cues but the women were not. Results also suggest that participants trained on the small angle (group 50°) used this cue effectively whereas participants trained on the large angle (group 75°) did not. However, this result was influenced by the sex of the participant, with the men being able to use the local cues regardless of the angle size; although the women in group 50° were more accurate compared to the women in group 75° this result was not significant, and neither group of women responded above chance during these tests.

A choice was considered correct if it was directed to a container positioned in front of an object projecting the correct training angle. For the variable of Group, participants trained on the small angle (group 50°) chose a correct container ($M = .77$, $SEM = .079$) significantly more often than would be expected by chance ($p = .003$, one-tail binomial test). In contrast, participants trained on the large angle (group 75°) did not choose a correct container ($M = .63$, $SEM = .089$) at a rate greater than would be expected by chance [($p > .05$, one-tail binomial test) see *Figure 4-3A*].

For the variable of Gender, men chose a correct container ($M = .83$, $SEM = .069$) significantly more often than would be expected by chance ($p < .001$, one-tail binomial test). Women, however, did not choose a correct container ($M = .57$, $SEM = .092$) at a rate greater than would be expected by chance [($p > .05$, one-tail binomial test, see *Figure 4-3B*]. Independent proportions z-tests showed that, for Group 50°, there was no difference in the proportion of correct choices made by men ($M = .80$, $SEM = .107$) compared to women ($M = .73$, $SEM = .118$, $z = 0$, $p > .05$, see *Figure 4-4*). However, the proportion of correct choices made by men was significantly greater than would be expected by chance ($p = .018$, one-tail binomial test), whereas for women the proportion of choices failed to reach significance ($p = .059$, one-tail

binomial test). For participants in Group 75°, men directed significantly more choices to a correct container ($M = .87$, $SEM = .091$) than women ($M = .40$, $SEM = .131$, z = 2.27, $p = .023$). The proportion of correct choices by men was significantly greater than would be expected by chance ($p = .004$, one-tail binomial test), but this was not so for women ($p > .05$, one-tail binomial test).

A)
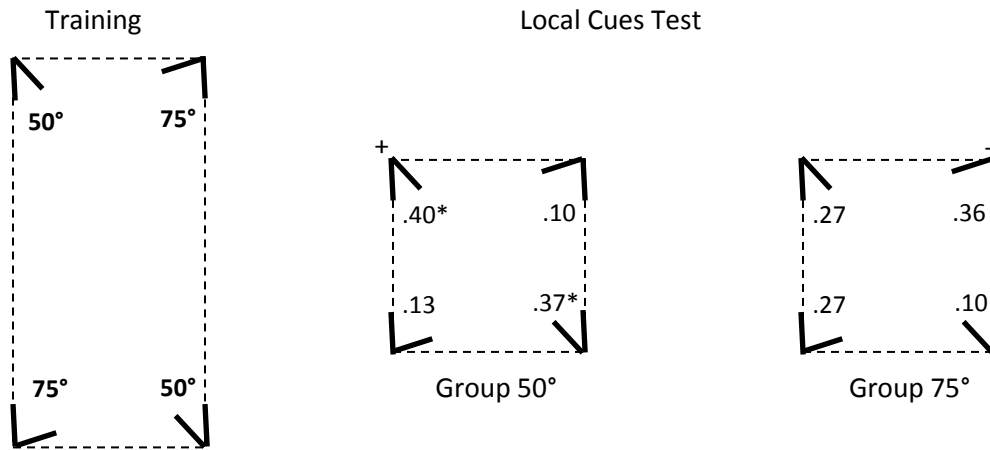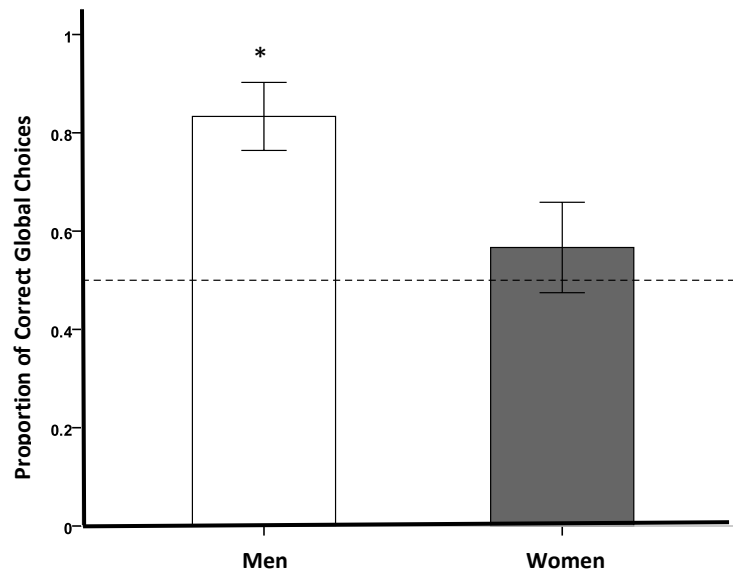
Figure 4-3. A) The leftmost schematic depicts the training setup indicating which objects projected the 50° or 75° angles. The middle and rightmost schematics show the distribution of choices for the Local Cues test based on training group. During testing the angles of the objects remained the same but the global shape of the array was converted to a square. For illustrative purposes the test figures depict either the top left object (for Group 50°) or the top right object (for Group 75°) as the object associated with the correct container (+), although this was counterbalanced during the experiment. B) Results for the main effect of Gender for the Local Cues test. Chance is indicated by the hashed line at 0.50.
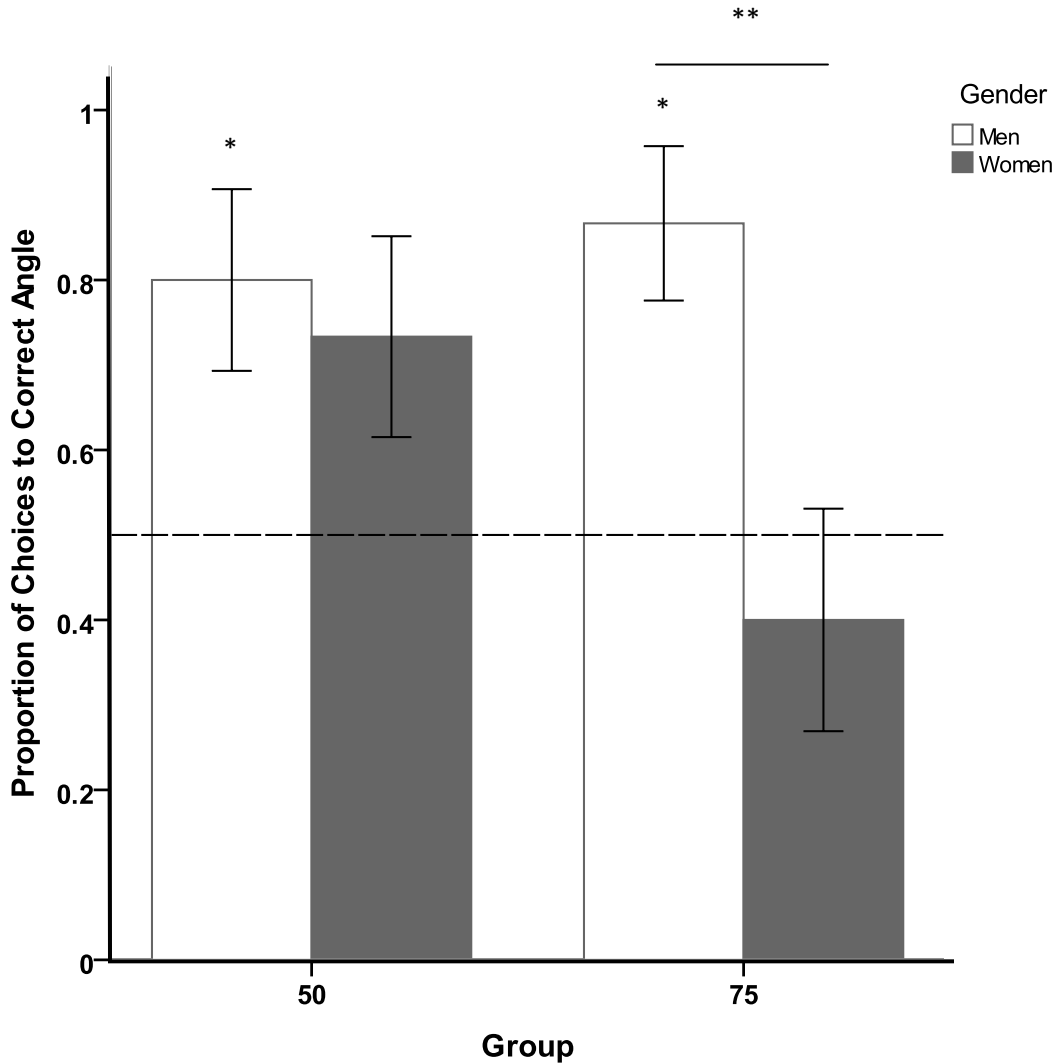
Figure 4-4. Proportion of first choices directed to the correct angle in the Local Cues test for men and women, within group 50° and group 75°. The * indicates the significant relationships (* = p < .05 and ** = P < .01).

Cue Conflict Test. Overall, results from the Cue Conflict test showed that men chose the local geometric cues over the global geometric cues at a rate higher than would be expected by chance whereas women showed no clear preference for either type of cue. A choice was considered correct if it was directed to a container positioned in front of an object projecting the correct training angle (Note: either the local or global response could be considered correct. We

chose the local cue as correct since neither men nor women encoded the global geometric cues –

see Global Cues test.) For the variable of Group, neither participants in group 50° (M = .53,

SEM = .093) nor group 75° (M = .50, SEM = .093) chose a correct container at a rate greater than

would be expected by chance (p > .05 respectively, binomial tests, see *Figure 4-5A*). For the

variable of Gender, men (M = .70, SEM = .085) chose the container associated with their correct

training angle significantly more often than would be expected by chance (p = .043, binomial

test) whereas women (M = .33, SEM = .088) did not [(p > .05, binomial test, see *Figure 4-5B*)].

A)

Training   Cue Conflict Test

| 50° | 75° |
| 75° | 50° |

| + |
| .20 | .27 |
| .26 | .27 |

| + |
| .27 | .23 |
| .27 | .23 |

Group 50°   Group 75°

B)

Figure 4-5. A) The leftmost schematic depicts the training setup indicating which objects projected the 50° or 75° angles. The middle and rightmost schematics show the distribution of choices for the Cue Conflict test based on training group. For illustrative purposes the test figures depict either the top right object (for Group 50°) or the top left object (for Group 75°) as the object associated with the correct container (+), although this was counterbalanced during the experiment. B) Results for the main effect of Gender for the Cue Conflict test.   Chance is indicated by the hashed line at 0.50.
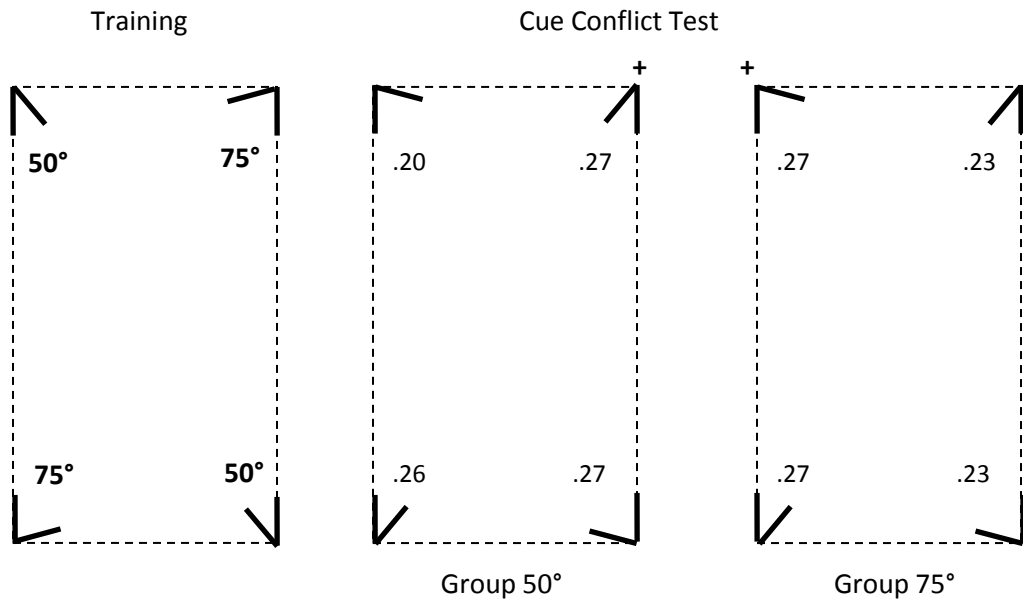
Independent proportions *z*-tests for Group 50° showed no difference between the proportion of choices directed to the containers located at the 50° angles by men ($M = .67$, *SEM* $= .126$) compared to women ($M = .40$, *SEM* $= .131$; $z = 1.1$, $p > .05$). However, for Group 75°, men directed significantly more choices to the containers associated with the 75° angles than women ($M = .73$, *SEM* $= .118$ and $M = .27$, *SEM* $= .118$, for men and women, respectively, $z = 2.19$, $p = .029$; see *Figure 4-6*). However, neither men nor women chose the containers associated with their correct training angle at a rate greater than would be expected by chance in either Group 50° or Group 75° ($p > .05$, binomial tests).
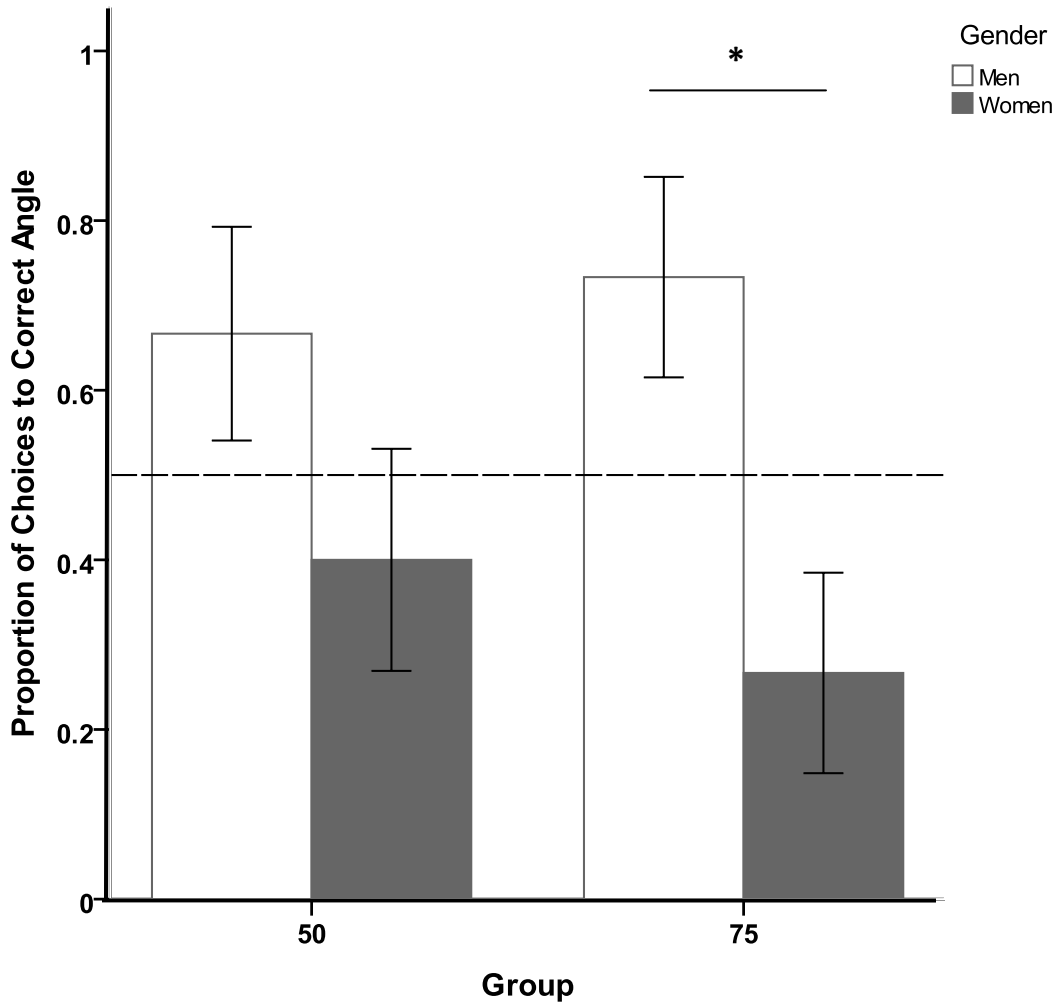
Figure 4-6. Proportion of first choices directed to the container associated with the correct angle in the Cue Conflict test for men and women within group 50° and group 75°. The * indicates the significant relationships (* = p < .05).

Discussion

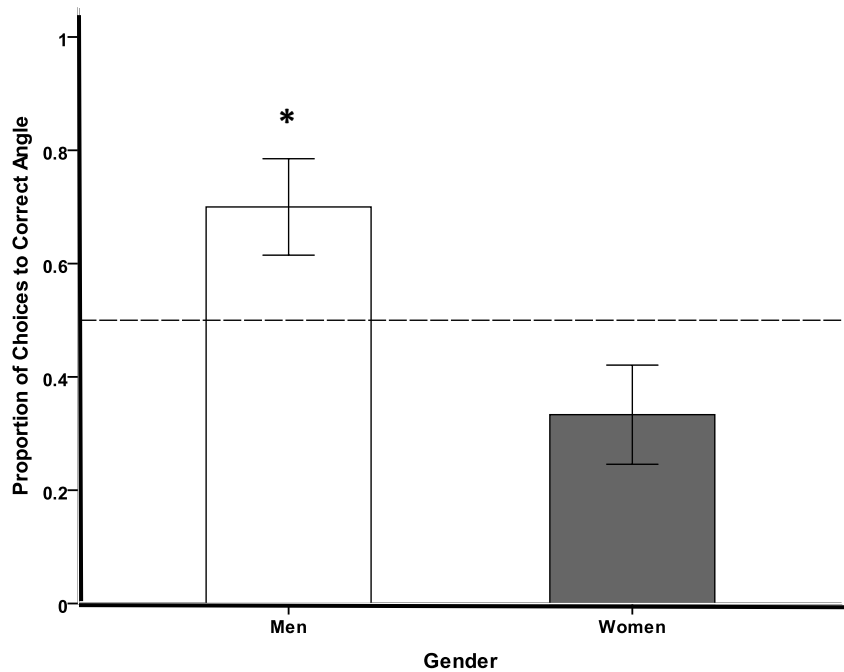Adult men and women were trained to locate one rewarded container from an array of four identical containers which were placed in front of objects presenting angular information. These objects projected one of two angles, either 50° or 75°, and provided the local geometric cues whereas the rectangular shape of the array provided the global geometric cues. To examine

whether the participants had encoded the local geometric cues, the global geometric cues or both, non-rewarded test trials were introduced which presented only the local cues, only the global cues, or both cues but providing conflicting information as to the goal location.

Overall, this task was difficult for the participants to learn as a large number of individuals were unable to meet our learning criteria (55/115 participants failed to meet criteria). The task was significantly more difficult for women compared to men. Our tests showed, that the majority of men may have solved the task by encoding the local geometry – learning to use the local angle associated with reward – whereas women did not show a strong encoding of either local or global cues. The results from the women are particularly surprising when one considers that so many more women needed to be recruited, compared to men, in order to obtain equal sample size for the two sexes. Thus, although our sample of women were more "selected" than men, the women that did pass training did not show a strong encoding of either local or global geometry.

Research has shown that poorer performance by women on spatial tasks may be influenced by non-spatial variables, such as higher levels of task-induced anxiety during route learning tasks (Lawton, 1994; Kallai, Makany, Csatho, Kazmer, Horvath, Kovacs-Labadi, et al., 2007). As our study was not designed to examine anxiety levels it is not known whether anxiety negatively affected women's performance. Future research examining whether task-anxiety differentially affects performance for the use of local and global spatial cues, by men and women, would further our understanding of whether non-spatial variables may influence the encoding of geometric information.

Encoding of Global Geometry. Surprisingly, considering previous research has shown that adult humans are able to use the configuration of an array of discrete objects to locate a hidden goal (Gouteux & Spelke, 2001), the participants in our study were unable to use the global shape of the array in the absence of distinctive local cues (Global Cues test).   When the local cues were made identical, and therefore uninformative, neither the men nor the women could use the rectangular shape of the array to guide their choices to the two geometrically correct corners, according to global geometry. One procedural difference between our experiment and that of Gouteux and Spelke (2001) is that, during our experiment, the object array was rotated on its central axis between trials, whereas it remained stationary in the study by Gouteux and Spelke. Reorientation experiments involving rotation of an array or the experimental space itself have resulted in an increased challenge to geometric encoding by children (Lourenco & Huttenlocher, 2006) as well as birds (Kelly, 2010).

 Furthermore, in our experiment the array was presented within a larger rectangular room, whereas Gouteux and Spelke's array was presented within a circular arena. Thus, the participants in our study might have had to learn that the shape of the room was not a reliable orienting cue. Given that humans (and many other species) show a strong tendency to encode the geometric properties from surfaces (or incidental encoding of geometry as argued by Doeller, King & Burgess, 2008), learning to ignore this strong geometric cue may have interfered with learning to use the global shape of the array. Indeed, using a virtual environment, Kelly and Bischof (2008) reported that adults showed a preference for using environmental geometry when array geometry and environmental geometry were placed in conflict.

 The differential encoding of global geometry from arrays and surfaces has certainly proven to be a rich area of study. For example, further evidence from virtual environments has

demonstrated that environmental boundaries may be processed incidentally whereas landmarks may be processed incrementally by means of associative learning (Doeller, King & Burgess, 2008). Support for this argument has also come from studies showing that rats with hippocampal lesions are impaired in their ability to use local geometric cues to navigate to the hidden platform within a rectangular-shaped pool in a water maze task (Jones, Pearce, Davies, Good, & McGregor, 2007). It would be interesting to examine whether the local angular information, as in our experiment, is processed as landmarks (associatively) or as environmental boundaries (incidentally).

Encoding of Local Geometry. Presenting the participants with a square array that preserved the local geometric properties (i.e., the angular information from the objects) showed that the men were able to use these local cues to limit their searches to the two correct corners, whereas women were not. Previous research has shown a robust sex difference in the use of spatial information, with men encoding geometric cues and women encoding featural information (e.g., Astur, Ortiz & Sutherland, 1998; Dabbs, Chang, Strong, & Milun, 1998; Kelly & Bischof, 2005; MacFadden, Elias, & Saucier, 2003; Sandstrom, Naufman & Huettel, 1998; and Saucier, Bowman & Elias, 2003). Our result adds to this growing literature.

One important contribution our present study adds to this previous research is that overall the men but not the women encoded local geometry. Typically, studies showing that men use the geometric properties of an environment (or Euclidean geometry) have examined the use of global geometry. For instance, Kelly and Bischof (2005) found that when men and women were asked to search for a hidden goal in a rectangular virtual environment with a distinctive feature in each corner, the men encoded geometry incidentally whereas the women did not. In our study, the local cues could have been encoded as local featural properties, thus giving women an

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advantage or as geometric information thus giving the men an advantage – our results suggest that the geometric information was extracted from these objects by the men, and not the women.

The finding that women did not use the local cues in our study conflicts with research showing that females readily use local information when it is made available to them in spatial tasks. Perhaps, the important difference in our study was that the local cues were geometric in nature and not featural, as has typically been used. For example, during a paper-and-pencil test of map learning and recall, women display a stronger reliance upon local landmarks than men when required to retrace a previously learned route (Galea & Kimura, 1993). When navigating a real-world environment, women are significantly impaired when forced to use a non-landmark, Euclidean geometry-based strategy, to learn the route from one location to another within a university campus (Saucier, Green, Leason, MacFadden, Bell & Elias, 2002). In a virtual version of the Morris water maze paradigm, women are adversely affected by the removal of local landmarks surrounding the pool, resulting in longer latencies to reach the hidden platform (Sandstrom et al., 1998). In computer-based reorientation research, Kelly and Bischof (2005) trained men and women to search at one corner of a three-dimensional rectangular room that provided both global geometry (the shape of the room) and local featural cues (colored objects at the corners). During testing, when the local featural cues were removed but the global cues remained, results showed that women had only encoded the local features during training whereas men had encoded both the local features as well as the global shape of the room.

We found an overall effect of angle size in the Local Cues test, with participants trained to search at the smaller angle (group 50°) using this angle more effectively than participants who had been trained on the larger angle (group 75°). When we examined whether both men and women contributed to this effect, we did not find a difference between the proportion of

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responses by men and women in group 50° – although only the men were significantly above chance. However, it should be noted that the accuracy of women in group 50° did approach significance ($p = .059$).

A possible encoding advantage of smaller angles relative to larger angles has been reported previously in research examining how chicks use local and global cues in walled enclosures. Tommasi and Polli (2004) trained chicks to find a food reward at one corner of a parallelogram-shaped apparatus. For one group of chicks, the walls at their rewarded corner joined to form an acute angle of 60° and for a second group of chicks, the walls at their rewarded corner joined to form an obtuse angle of 120°. Although the chicks in both groups could use either the corner angles or the walls in isolation, during conflict testing when the chicks were forced to choose between the relative lengths of the walls and the angle subtended by those walls at their positive corner, group differences were found. Specifically, chicks that had been trained to search at corners projecting smaller angles continued to search in the corners with small angles even though the relative lengths of the adjoining walls were now incorrect according to training. In contrast, chicks that had been trained to search at corners projecting larger angles searched at corners that preserved the correct length of walls from training, even though these corners now projected smaller angles.

The results from Tommasi and Polli (2004) suggest that, for chicks, smaller angles represent stronger orientation cues than larger angles in walled enclosures. These findings are interesting in relation to our study because they suggest that smaller angles may be more useful to a disoriented organism than larger angles when they are presented in the context of either a walled enclosure or an object array. The reason for this discrepancy in angle strength remains

unclear. Tommasi and Polli suggested that smaller angles may be more perceptually distinctive than larger angles. This may have also been true for our study.

An alternative explanation for the advantage of smaller angles in our study is that the participants were using the distance between the two edges and not the actual angular information itself. If this were the case, the larger distance between the two edges of the 75° object would have been less perceptually discriminable than the smaller distance between the two edges of the 50° object – a result supported by Weber's law which states that the amount of change needed to detect a just noticeable difference is proportional to the magnitude of the original stimulus (Barlow, 1982, and evidenced in the spatial realm by Cheng, 1992). However, the argument that smaller angles may be more perceptually salient than larger angles in our study, must be interpreted with caution because the men performed better than chance with both the 50° and 75° angles; it was only when examined at the group level (performance of men and women) that small angle effect was significant.

Cue Conflict. Results from the Cue Conflict test showed that men searched at their training angle, even though it was now located in an incorrect position according to global geometry, at a higher rate than would be expected by chance. Although the men in both groups chose the containers associated with the training angle, only the men in group 75 did so more often than chance. Thus, this test further suggests that the local geometry was guiding the men's encoding of the array and not the global cues. Indeed, the results from the Global Cues test suggest that without the encoding of the global geometry, this was likely not even a cue conflict situation.

Previous research using object arrays has shown a facilitation effect for global shape encoding when the objects comprising the array are visually distinct from one another. Thus, it is interesting that we did not find facilitation in our study. For example, Gouteux and Spelke (2001) found that children could not recognize the configuration of four identical objects, but they could use this information when the objects were each uniquely colored. The same pattern of results was obtained in a similar task using a rectangular array of identical objects with Clark's nutcrackers (Kelly, 2010), a long-term food storing bird known for its accuracy and flexibility when using geometric cues (Kamil & Jones, 2000). Rats have also been shown to learn the geometric configuration of an array of identical discrete objects when trained with uniquely coloured objects (Gibson, Wilks, & Kelly, 2007). Our current study differs from these previous investigations of feature arrays in that each of the cues was not distinctive, but rather cues in geometrically equivalent corners were identical. Taken together, these results suggest that successful encoding of distinct local cues serves to simultaneously facilitate encoding of global geometric properties of discrete object arrays. However, there are possible reasons as to why this did not occur in the present experiment.

One possibility is that only local featural cues (e.g., shape or color) facilitate encoding of global shape properties, whereas local geometric cues may compete for associative strength – however, this speculation must be tested.

A second possibility is that the global geometry was encoded in combination with the local geometry, and when the angles of the objects were transformed to a novel angle of 90° during the Global Cues test, the ability of participants to use the shape of the array alone was impaired – or the novel angles interfered with choice behavior. This suggests that successful encoding of the global geometry of the object array may have been contingent upon the local

geometry maintaining a measure of consistency between training and testing. That men were able to use the local cues during the Local Cues test, when the shape of the array had been converted to a square, suggests that changing the global geometry did not negatively influence the ability of the men to use local geometric cues.

A final possibility is that the nature of the objects comprising the array may have reduced the salience of its overall shape. Specifically, the disparate angles of the objects may have prevented the array from being encoded as a global shape. Previous studies using object arrays have typically used symmetrical objects – allowing an imaginary line to be drawn straight from the side of one object to the next. This was not so with our array as our objects were positioned such that only one edge of the object aligned with another; the other edge was positioned such that a straight alignment with another object's edge was not possible (see Figure 4-1A). The only means of achieving an overall global shape would be to enclose the objects at the apex of the angles (as our dashed lines in Figure 4-1A indicate). Thus, attaining a global representation of the array might have been less salient than the local geometric cues.

Conclusions

We examined the encoding of both local and global geometric cues of a discrete object array by adult humans. Men and women were tested on their ability to use local and global geometric cues to locate a hidden goal within a four-object rectangular array. Contrary to previous research, neither men nor women used the global geometry provided by the shape of the array to reorient. However, when tested with only the local angle cues available, the men, but not the women, were able to use these cues to search accurately. These findings are consistent

with comparative studies with children and non-human animals showing increased difficulty with configuring object arrays.

A key issue that remains for future study is whether local geometric cues are encoded differently than local featural cues. There are two lines of evidence in the present study to suggest a profound difference in how local geometry is processed compared to local features. Firstly, the fact that men had clearly encoded the local angles but failed to encode the global shape of the corresponding array does not fit with previous research which suggests that distinctive featural cues may facilitate the encoding of global geometry from arrays. Indeed, our results raise the question of whether the local geometric cues competed with the encoding of the global geometry. Future research equating for cue saliency will be needed to resolve this issue. Secondly, the finding that women were unable to use the local geometric cues contrasts with previous findings showing that women use local featural cues in both reorientation and navigation tasks. This was certainly not the case in our experiment. Further research is required to better understand the relationship between local and global geometric cues and how they are learned and processed within both walled enclosures and object arrays.

CHAPTER FIVE

General Discussion

The goal of this thesis was to examine whether learning strategies of geometric angles depend upon the size of the angle in question. The angles could either be learned absolutely whereby they would be perceived as more distinct and exact or they could be learned relationally based on how small or large they appeared alongside comparison angles. In order to better understand the nature of the angle encoding, a comparative approach was undertaken using both pigeons and humans as subjects. Both these species have previously shown differences in geometric cue learning, with pigeons more readily adopting absolute learning strategies and humans more inclined toward relational learning. Through the use of both a visual discrimination paradigm as well as a reorientation paradigm the learning and use of geometric angles as spatial cues was examined.

In the study contained in Chapter 2 pigeons were trained in an open-field task to discriminate between a small angle and a large angle. Pigeons were grouped based upon whether they were rewarded for choosing either the small (60°) or the large angle (120°) during training. During testing, the birds were provided with a choice between their training angle and a novel test angle that was either smaller or larger than their training angle. The pattern of responses suggest that birds trained to choose the small angle showed a more absolute learning pattern than birds trained to choose the large angle. Specifically, the small angle group generalized their responses such that the test angle that received the highest rate of responses was slightly smaller (40°) than the training angle of 60°, a response typical of absolute encoding (Spence, 1937). In

contrast, birds trained to choose the large angle did not show this pattern, instead choosing all test angles larger than their training angle of 120° at an equivalent rate. These results suggest that the small angle was perceived by the pigeons to be more distinctive – and therefore more resistant to broader generalization – than the large angle.

During Experiment 1 contained in Chapter 3, adult humans were trained and tested with the same type of angle discrimination task, but the training angles used were 50° and 75°. One group of individuals was trained to choose the smaller angle and a second group was trained to choose the larger angle. During testing each group was provided with a series of direct comparisons between their training angle and a novel test angle. Just as with the pigeons during Chapter 2, people trained to choose the smaller angle showed evidence of an absolute learning pattern whereas people trained to choose the larger angle did not. These results are consistent with the conclusion that smaller angles were being perceived as more distinctive than larger angles. Experiment 2 extended these findings by adding a third, smaller training angle (25°) to the original two (50° and 75°) thus allowing the learning pattern of an even smaller angle to be examined; additionally, the inclusion of a middle training angle (50°) allowed for an examination of responding when a clear relative relationship was not available (i.e., it was smaller than one training angle but larger than the other). Results from Experiment 2 showed an absolute learning pattern for the smallest angle that was even more pronounced than that of the smallest angle in Experiment 1, suggesting that the smaller an angle becomes the more distinct it becomes as well. Results from Experiment 2 for the group trained to choose the middle angle (50°) showed that they were very accurate when choosing this angle during testing, with no evidence of biased generalization to angles either above or below this value.

The study contained in Chapter 4 was designed to take the knowledge obtained about angle discrimination and apply it to a spatial learning task. People were trained to search for a hidden reward located in front of one of four objects arrayed in the configuration of a rectangle. Each object was constructed by two identical pieces of wood joined with a hinge such that they could expand and contract to form unique angles; diagonally opposite angles (either 50° or 75°) were identical and people were group based upon the size of their training angle. The spatial cues inherent in this task were strictly geometric in nature, with the global shape of the object array and the local geometry of the angles being the only cues available as to the location of the hidden reward. Although people had difficulty learning the shape of the array they could use the information from the angles to reorient, as evidenced by a test in which the array was configured in the shape of a square (i.e., absent of global cues present from training), but the local geometric cues (the angles) preserved. However, the participants' ability to use the local angles was dependent upon angle size, with individuals who had been trained to search at the smaller angle able to use this angle more accurately than those who been trained to search at the larger angle. These findings are consistent with the prior discrimination results found in Chapters 2 and 3 showing that smaller angles appear to possess a higher level of distinctiveness than larger angles based upon the absolute learning pattern elicited by smaller angles.

What might be the reason for differential learning of smaller and larger angles? A likely possibility is that the edges that form smaller angles are closer together than they are for larger angles, providing a more reliable visual measurement of the angle size thus making it easier to distinguish. As the edges of larger angles are moved further apart this ability to make precise judgements on the size of the angle becomes increasingly difficult. These differences in judgement may be at the root of the different learning strategies being shown: as the angle

becomes larger the sureness of its exact size is lessened and thus the chance of it being learned absolutely is reduced accordingly. This possibility is consistent with the tenets of Weber's law whereby the amount of change needed to perceive a minimally perceptual difference is directly proportional to the magnitude of the original stimulus (Barlow, 1982). In order to understand whether more precise encoding is solely a product of smaller angles, future research should examine learning patterns when training angles consist of obtuse angles only to determine whether similar encoding strategies can be induced when all training angles are of a larger variety.

Collectively, these results are important because they show differential learning and use of geometric angles dependent upon size whereby smaller angles are perceived as being more distinctive and consequently more reliable spatial reorientation cues. Preferential learning of smaller angles compared to larger angles has been shown previously with domestic chicks during a reorientation task conducted inside a parallelogram-shaped structure in which one set of diagonally opposite corners projected 60° angles and the other set projected 120° angles (Tommasi & Polli, 2004). In that experiment, when the chicks were tested in a rhombic environment whereby only the angle cues remained (the walls were all of equal length) the chicks could easily recognize and use the corner angles. However, when tested in a mirrored version of the training parallelogram in which the wall properties and angle properties were placed in conflict such that the chicks could freely choose either as their preferred cue, the chicks trained to search at the small angle preferred to search at corners that maintained this angle whereas chicks trained to search at the larger angle preferred corners that maintained the correct wall properties instead. Thus, for domestic chicks, the smaller corner angles seem to hold more salience than the larger angles, results consistent with the present set of studies.

Aside from the findings with domestic chicks provided by Tommasi and Polli (2004) there has been scant research that has specifically examined the use of geometric angles within spatial tasks, although the learning and use of local geometric properties such as angles is an area of spatial cognition that is garnering increased interest. In research conducted by Hupbach and Nadel (2005) small children were disoriented and then trained to search for a toy that they had watched being hidden at one corner of a rhombus-shaped environment in which all the walls were of equal length but one set of diagonally opposite corners projected identical smaller angles and the other set of a corners identical larger angles. Thus, global geometry was held constant (and uninformative) whereas local geometry could be used to locate the toy with either the child's first or second choice during a single trial since diagonally opposite corners were geometrically indistinguishable. Results showed that children could use either size of angle to search correctly, thereby displaying no learning advantage for either the smaller or larger angles, although it should be noted that no type of cue preference test was conducted. It has also been shown in water maze research with rats that local geometric properties can be extracted from the shape of the greater environment - in this case a kite-shaped pool – and used as independent cues when transferred to a rectangular-shaped pool (Pearce, Good, Jones, & McGregor, 2004). Although these results clearly show, as do the results from Chapter 4, that local geometry in the form of corner angles or wall length can be learned independent of global geometry, the nature of the learning of these cues is not known, making the angle discrimination results from the current Chapters 2 and 3 particularly illuminating in this regard. The notion that certain geometric properties may lend themselves to featural-like learning principles is a concept that runs contrary to traditional thinking of how geometry and features are encoded and as such is an area that requires much more investigation.

The idea that features and geometry within an environment may be subject to different types of learning is not new. Using a virtual environment, Doeller, King, and Burgess (2008) found that the learning of a goal location relative to a landmark was different than learning its position relative to the geometric boundary of the environmet. Similarly, in research with rats using the Morris water maze, a featural beacon positioned directly above the hidden platform did not prevent rats from learning to use the environmental geometry to locate the platform (Pearce, Ward-Robinson, Good, Fussell, & Aydin, 2001). These findings suggest that environmental geometry may be learned implicitly whereas featural or landmark learning occurs through associative means on a trial by trial basis. It is for this reason that principles of associative learning such as overshadowing and blocking (Miller, Barnet, & Grahame, 1995; Rescorla & Wagner, 1972) are much more common within the realm of featural learning (Hayward, McGregor, Good, & Pearce, 2003; Rodrigo, Chamizo, McLaren, & Mackintosh, 1997; Spetch, 1995) than they are for geometric learning and exceptions are infrequent.

Although evidence of overshadowing of environmental geometry by featural cues has been shown for black-capped chickadees (Gray, Bloomfield, Ferrey, Spetch, & Sturdy, 2005), this account was weakened by subsequent studies which modified the original procedures (how the featural cues were presented) and subsequently showed that the environmental geometry was indeed learned (Batty, Bloomfield, Spetch, & Sturdy (2009). Contrarily, the fact that a diverse range of species can successfully and spontaneously encode the geometric shape of a space to reorient (see Cheng & Newcombe, 2005 for review), even in the presence of salient features, speaks to the resilience of geometric learning, at least as it applies to continuous flat surfaces. However, the current results suggest a further distinction in the learning that occurs between local geometric cues by showing differential encoding of smaller and larger angles. Specifically,

our the current findings show that smaller angles were encoded more absolutely, and thus featural-like, directly opposes the theory of the geometric module (Cheng, 1986; Gallistel, 1990) which posits a clear separation between geometric and featural cues.

Given that the global geometry of a walled space is both readily learned and largely resistant to associative competition from featural cues the question becomes, do the same principles then apply to local geometry such as corner angles? Since these have been shown to be encoded as spatial cues in their own right [(Hupbach & Nadel, 2005; Tommasi & Polli, 2004) (Chapter 4 of the current research)] and local geometry can be successfully extracted and learned independent of the global shape of the space (Pearce et al., 2004), an intriguing question is whether the learning of local corner angles can be influenced by the presence of salient featural cues. For example, a parallelogram-shaped enclosure with different-colored walls provides both local geometry as defined by the corner angles and featural cues as defined by the different colors of the walls. If smaller angles are indeed more prone to featural-like learning than larger angles as the studies incorporated within this thesis suggest, it would then be expected that competition from featural cues would inhibit the learning of larger corner angles more so than the more distinct and salient smaller corner angles. Cue competition involving the inhibited learning of geometric properties would also provide strong evidence against the presence of a geometric module that is theoretically resistant to associative pressures provided by features.

A second way to determine whether smaller angles possess qualities more closely associated with features would be through the use of an object array. As noted previously, the learning of environmental geometry is enhanced considerably through the presence and continuity provided by walls, and when geometry is instead presented as a configuration of discrete objects different behaviour is elicited. For example, the geometric configuration of an

array of identical discrete objects can often be difficult if not impossible for different animal species to discern, as evidenced in pigeons (Spetch et al., 1997), Clark's nutcrackers (Kelly, 2010), marmoset monkeys (MacDonald, Spetch, Kelly, & Cheng, 2004) and even human children (Gouteux & Spelke, 2001). However, when distinct features are used instead to make up such an array its geometric shape can then be learned (Kelly, 2010; Spetch et al., 1997). Therefore, in the case of object arrays, featural cues aid in facilitating the encoding of geometry, thereby serving a complementary role in relation to geometry. However, all of the findings supporting this in object arrays have involved global geometry; the effect of features on the learning of local geometry is not yet known. If features and geometric angles were presented together within the context of an object array would a similar facilitation effect occur or would there instead be cue competition? Moreover, would the same effects be found for small and large angles?

In order to fully examine the different possibilities in which geometric angles can be utilized as spatial cues a comparative approach is necessary given the diverse ways in which different animal species often approach spatial problems, particularly as it pertains to environmental geometry. Additionally, human developmental research has proven to be a valuable field in which to look for differences in geometric and featural encoding. For example, very young children have shown a delayed sensitivity to spatial features (Hermer & Spelke, 1994). With this in mind, do small children perceive smaller angles similarly to features and, if so, is this behaviour age-dependent as it is with other spatial features? Another promising area of future study in involves human sex differences whereby men and women show diverse behaviour in spatial learning (Sandstrom, Kaufman, & Huettel, 1998; Saucier, Green, Leason, MacFadden, Bell, & Elias, 2002). Although the study contained in Chapter 4 of the current

thesis found evidence suggesting a male advantage in the use of local geometric angles during reorientation these results were not borne out in the human discrimination research of Chapter 3. However, given that men and women show differential use of environmental features and geometry, with men typically exhibiting a stronger ability in the use of geometry, more research into how this behaviour relates to the encoding of different geometric angles is needed. Another area of interest that deserves further investigation is the possibility of enhanced geometric encoding by specialized populations for whom environmental geometry plays a more prominent role in their daily lives. Examples of such populations would include architects and engineers who may possess a more finely tuned ability to recognize differences in geometric angles and distance separations. As well, outdoor enthusiasts such as skiers who need to sight potential avalanche zones, may develop skills that enable them to recognize angles of dangerously-sloped snow accumulation along mountainsides.

In summary, the results from Chapters 2 and 3 showed that smaller geometric angles were learned differently than larger angles, with smaller angles encoded more absolutely and larger angles more relationally; Chapter 2 showed this pattern in pigeons and Chapter 3 showed this pattern in adult humans. The encoding similarities evident from this species comparison is notable given that pigeons and humans have shown behavioural differences when encoding geometry during spatial search tasks – specifically, pigeons have been shown to encode environmental geometry in absolute terms whereas humans have shown relational encoding (Spetch et al., 1997). Additionally, during discrimination tasks using simple stimuli that differ along a single dimension (e.g., light wavelength, line length), pigeons show absolute learning whereas humans are strongly driven to develop a relational rule and then follow it (MacIntosh, 1997). Therefore, the fact that both pigeons and humans show absolute encoding patterns for

smaller angles but not for larger angles provides compelling evidence for different sizes of

angles being susceptible to different types of learning. The study contained in Chapter 4 directly

tested this possibility in a spatial task by examining the ability of adult humans to use different

sized angles as reorientation cues. Tellingly, results from this study showed that people were

more able to use smaller angles to reorient as opposed to when they were using larger angles,

suggesting that smaller angles may have been perceived as being more distinct and salient. The

results from Chapter 4 are therefore consistent with those of Chapters 2 and 3 which suggest

absolute learning of smaller angles but not larger angles. Overall the findings from these three

studies reported in Chapters 2 through 4 suggest that smaller geometric angles may be perceived

more distinctly than larger angles and that this distinctiveness may result in more efficient use of

smaller angles during the course of a spatially-based task, in this case spatial reorientation.

Moreover, the collective results from this research hint at the novel prospect that smaller angles,

unlike larger angles, may be learned and utilized less like geometric cues and more like featural

cues, findings that run contrary to the modular theory of geometric encoding whereby the

processing of geometry and features remain mutually exclusive.

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