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Reorientation in a Two-Dimensional Environment: I. Do Adults Encode the Featural and Geometric Properties of a Two-Dimensional Schematic of a Room?

Debbie M. Kelly and Marcia L. Spetch
University of Alberta

Adults searched for a goal in images of a rectangular environment. The goal's position was constant relative to featural and geometric cues, but the absolute position changed across trials. Participants easily learned to use the featural cues to find the target, but learning to use only geometric information was difficult. Transformation tests revealed that participants used the color and shape of distinct features to encode the goal's position. When the features at the correct and geometrically equivalent corners were removed, participants could use distant features to locate the goal. Accuracy remained above chance when a single distant feature was present, but the feature farthest from the goal yielded lower accuracy than one closer. Participants trained with features spontaneously encoded the geometric information. However, this representation did not withstand orientation transformations.

One important step for successful navigation is determining the appropriate direction to travel. This has been referred to as determining one's heading (Gallistel, 1990). Research has shown that animals may use many different mechanisms and environmental cues to accurately orient, including self-referencing systems such as path integration and external referencing systems based on landmarks or environmental geometry (e.g., Healy, 1998). However, if self-referencing systems are disrupted and the animal is disoriented (e.g., by rotation), the animal will need to rely on external cues to reorient. Several studies have suggested that external landmarks and/or the overall geometric shape of the environment may be used in this process of reorienting (Cheng, 1986; Cheng & Gallistel, 1984).

Cheng's (1986) pioneer experiments with rats proposed the idea that animals may be able to use the geometric shape of their surrounding environment to recover a correct heading following disorientation. Cheng trained rats to locate food that was hidden in a rectangular enclosure. The location of the food varied across trials. The rat was allowed to find and eat half of the food and then was removed from the chamber. The remaining portion of the food was hidden in the same location but in a replica of the original training chamber. The rat was placed into the replica chamber to find the hidden food. To disrupt inertial cues, and thus require the rats to reorient while within the enclosure, the rats were rotated prior to being released back into the apparatus. Interestingly, although the enclosure had distinctive featural cues in each corner (i.e., different olfactory, visual, and tactile cues), the rats did not show control by the features, but rather they chose the correct corner and the corner diagonally opposite to the correct corner equally often. Furthermore, when rats were trained on a reference memory version of the task, although able to use the featural cues, they still chose the diagonally opposite corner more than expected by chance. Cheng termed these choices to the diagonal corner "systematic rotational errors." The presence of such systematic rotational errors showed that the rats had not encoded the distinctive features but rather were using the overall shape of the enclosure (i.e., geometric cues). This was surprising, because if the rats had encoded the featural cues, they would have been able to use this information to consistently locate the hidden food. However, because a rectangular structure is symmetrical, using geometric information alone only allowed the rats to narrow down their choices to the two *geometrically* correct corners.

In the years following Cheng's initial experiment, several investigators adopted (and modified) this approach to examine whether other species, including humans, are able to use geometric information supplied by the shape of their environment and conjoin this information with featural cues (e.g., fish, Sovrano, Bisazza, & Vallortigara, 2002; rats, Benhamou & Poucet, 1998; Margules & Gallistel, 1988; pigeons, Kelly, Spetch, & Heth, 1998; chicks, Vallortigara, Zanforlin, & Pasti, 1990; rhesus monkeys, Gouteux, Thinus-Blanc, & Vauclair, 2001; human adults and children, Hermer & Spelke, 1994, 1996; for a review, see, Wang & Spelke, 2002).

Hermer and Spelke (1994) used a paradigm similar to Cheng's to examine whether human adults and young children (ages 18 to 24 months) encode geometric and featural properties of a rectangular environment. An object was hidden in one corner of a rectangular room while the participants watched. The participants

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Debbie M. Kelly and Marcia L. Spetch, Department of Psychology, University of Alberta, Edmonton, Alberta, Canada.

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Correspondence concerning this article should be addressed to Debbie M. Kelly, who is now at the Department of Biological Sciences, University of Nebraska—Lincoln, 348 Manter Hall, Lincoln, NE 68588-0118. E-mail: dkelly@unlserve.unl.edu

were then asked to close their eyes and rotate in circles (some of the children were rotated either by the experimenter or their parent) before searching for the hidden object. Perhaps unsurprisingly, the adults were very accurate at finding the hidden object, indicating they had encoded the featural properties in the environment. Furthermore, when all of the distinctive features were removed from the environment, the adults could use geometric information alone to limit their searching to the two geometrically correct corners. What was not an intuitive result was that the young children were not able to use the featural information to locate the hidden object. Rather the children showed strong control by the geometric information, dividing their choices between the two geometrically correct corners. The authors suggested that these results indicate that children must have some type of innate geometric module and that with development the geometric module may be overridden to allow for the conjoining of geometric and featural information. Additional support for the idea that development is needed for humans to conjoin geometric and featural information comes from studies that investigated reorientation with older children, specifically children that already possess spatial language abilities (3- to 7-year-olds, Hermer-Vazquez, Moffet, & Munkholm, 2001; 6- to 7-year-olds, Hermer-Vazquez, 1997). Furthermore, in a study in which adults were required to maintain a verbal shadowing task while searching for the hidden goal, participants did not show encoding of featural cues (Hermer-Vazquez, Spelke, & Katsnelson, 1999). However, the claim that spatial language is needed for conjoining geometric and featural information requires further investigation in light of the many studies showing that several nonlinguistic animals can integrate these two sources of information (e.g., fish, Sovrano et al., 2002; pigeons, Kelly et al., 1998; chicks, Vallortigara et al., 1990; rhesus monkeys, Gouteux, Thinus-Blanc, & Vauclair, 2001).

Another challenge to the suggestion that linguistic development underlies the transition from reliance on a geometric module to conjoining of geometric and featural information comes from recent demonstrations that the spatial scale of the environment in which the children are tested can also play an important role in the use of featural cues (Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, & Huttenlocher, 2001). Learmonth et al. (2001) found that children of similar ages to those participating in Hermer and Spelke's (1994) study were able to conjoin geometric and featural cues to accurately locate a hidden object in a rectangular room. The authors suggested that the main procedural difference between their study and that of Hermer and Spelke was the size of the experimental room. A follow-up study by Learmonth et al. (2002) directly compared the use of geometric and featural cues by young children (36–59 months) within two different room sizes. One of the rooms was the same size as used by Hermer and Spelke and the other was the same size as the room used by Learmonth et al. (2001). The investigators found that children tested in a small room relied exclusively on geometry (supporting Hermer & Spelke's account), whereas children tested in a larger room were able to conjoin both geometric and featural cues (supporting Learmonth et al., 2001). These studies suggest that environmental size is an important aspect that requires closer examination in the attempt to understand the mechanisms of spatial reorientation and the possibility of a purely geometric module.

Many investigators have been interested in understanding how the nature and scale of the spatial environment influence how information is encoded. Research has shown that people may use different sources of information when presented with a physically navigable environment, a model representing a navigable environment, or a maplike view of the environment (Cohen, 1985). Only recently has the use of a geometric module been examined using models of an environmental space (Gouteux, Vauclair, & Thinus-Blanc, 2001). Gouteux et al. (2001) investigated the use of geometric and featural cues by adults and young children (3-, 4-, and 5-year-olds) when searching for a hidden goal in a model of a rectangular room (less than 1 m in size). As discussed by the experimenters, using a model instead of an actual room changes several aspects of the task. Some of these differences include the following: The participant passively views the environment instead of locomoting through it, the entire space may be viewed from a single vantage point, the apparatus and not the participant is rotated across trials, and several stable extraenvironmental cues are available to the participant. However, despite these many differences, the investigators found remarkable similarities between this model room and previous studies using a real room. Gouteux et al. found that the younger children (4- and 5-year-olds but not 3-year-olds) used the geometric information by showing systematic rotational errors. Furthermore, the 5-year-old children were able to conjoin featural and geometric cues to concentrate their searches to the correct corner. Interestingly, although the researchers found a similar pattern of developmentally driven cue use, the abilities appeared to emerge slightly later in the model environment. Whereas previous studies reported that 3-year-olds could use geometric information to orient within a real environment, this ability was seen a bit later in the Gouteux et al. study; the 3-year-olds were not able to orient by either nongeometric or geometric cues in the model environment, and the conjoining of geometric and featural cues was not seen until the age of 4 (but even at age 5 the children were not as accurate as the adults). Thus, the investigators concluded that the ability to use geometric information and the ability to conjoin featural and geometric information in a small-scale model task might develop later than when using a navigable task. As in previous studies, the adult participants were very accurate at locating the correct corner. However, the authors did not examine whether participants would spontaneously encode geometry when trained in the presence of features.

In our study, we examined adult humans' use of geometric and featural cues using a more maplike task by presenting images of a schematic rectangular environment to participants. Although several studies have examined landmark use by adults using images presented on a computer monitor (e.g., Spetch, 1995; Spetch, Cheng, MacDonald, 1996; Spetch et al., 1997), none of these studies has examined whether adults are able to use geometric information from continuous surfaces, or whether adults can conjoin geometric and featural cues when these cues are two-dimensional (2-D). Furthermore, these previous studies have presented the featural information or landmarks within a directionally stable search space in that the orientation of the landmark array on the computer screen was consistent across trials. In our experiments, stable extraenvironmental cues were present, but these did not provide a useful directional frame of reference because the rectangular environment was rotated between trials. Understanding if, and how, adult participants can conjoin geometric and featural information presented using a 2-D medium is important given the increased use of this type of task in examining human spatial cognition and navigation.

Experiment 1

In this first experiment, we examined whether adults could use the featural and geometric cues to find a hidden goal in a schematic of a rectangular room. This task is quite different from investigations of geometric encoding in real three-dimensional (3-D) environments in that (a) the environment was a schematic of a rectangular room and, as such, only 2-D cues were available, (b) the participant remained stationary while the geometric room was rotated across trials (this rotation was not visible), and (c) several stable extraenvironmental cues were always available but were not useful as directional cues because of the rotation of the geometric room. The purpose of Experiment 1 was to examine whether participants could learn to use the featural and geometric cues of the schematic room. We also included tests to rule out the use of other strategies to solve the task (e.g., absolute positions on the computer screen).

Method

Participants

The participants were 32 undergraduate students from the University of Alberta, Edmonton, Canada. Twenty-six women and 6 men (ages ranged from 17 to 41 years old and 19 to 26 years old, respectively; average age = 22.9) participated in the experiment to obtain credit for their introductory psychology course. Participants were randomly assigned to either a group in which first the feature and then the geometry training and testing were given (group F–G; 12 women and 4 men) or a group in which first the geometry and then the feature training were given (group G–F; 14 women and 2 men), with the constraint that each group had to have an equal number of participants (16 participants per group). Once assigned to a group, each participant was randomly assigned to one of four image-rotation subgroups (see explanation in the *Procedures* section), with the constraint that each image-rotation subgroup had 4 participants. Within each subgroup, the corner of the rectangle that was designated as correct was counterbalanced across participants.

Apparatus

The experiment took place in a small private room. Each participant sat on a chair in front of a computer monitor (Zenith 1490) equipped with a touch-screen (Carroll Touch 1490 Smart Frame). All participants' choices were made by their directly touching the screen with the eraser end of a pencil. Pressing any key on the keyboard that was located directly in front of the monitor advanced the trials.

Images

All images presented a gray rectangular environment centered on a white background (see Figure 1). Four identical black response squares were located at the corners of the rectangle, and up to four features (uniquely colored shapes) were presented adjacent to the corners. The environment was approximately 3 × 5 cm (depending on the type and number of features present). The gray rectangle was 2 × 4 cm. Each black response square measured 0.5 × 0.5 cm. Because the number and type of features varied with training and testing conditions, these are explained in more detail in the *Feature training* and *Feature testing* sections.

Design

The design of the experiment was a mixed-factor design (see Table 1). The two between-subjects factors were Training Order (two levels: group F–G and group G–F) and Image-Rotation Subgroup (four levels: 0–180, 45–225, 90–270, and 135–315). The participants in group F–G were trained with the feature condition and then received the following tests: Feature Control, Color-Only, Shape-Only, Move, and No Shading. They were then retrained with the geometric condition and received the following tests: Geometric Control, Move, and No Shading. The participants in group G–F were trained with the geometric condition and then received the following tests: Geometric Control, Move, and No Shading. They were then retrained with the featural condition and received the following tests: Feature Control, Color-Only, Shape-Only, Move, and No Shading (see Table 2 for a summary). The specific details of the training and testing conditions are provided in the appropriate *Procedure* section.

General Procedure

All participants were trained and tested individually. Once seated in front of the computer monitor, participants were provided with the following information:

They would see a series of images presented one at a time. In these images they would always see four black squares. Their task was to determine which square was "correct" and touch that square with the eraser end of their pencil. Once they touched the square the image would disappear and a screen would appear indicating (a) they had chosen the correct square and had been awarded a point, (b) they had chosen an incorrect square and therefore had not been awarded a point, or (c) no feedback was available for this particular trial. Participants were told that no feedback did not mean they were correct or incorrect, it simply meant that no feedback was available. Pressing any key on the keyboard would remove the feedback screen and present the next image. Participants were told that they should try to accumulate as many points as possible. They were then asked whether they had understood all the instructions and whether they had any questions. The experimenter also informed the participants that they could stop participating at any time without penalty, and should they choose to participate, the session would end after they had accumulated a predetermined number of points or after 45 min had elapsed, whichever came first.

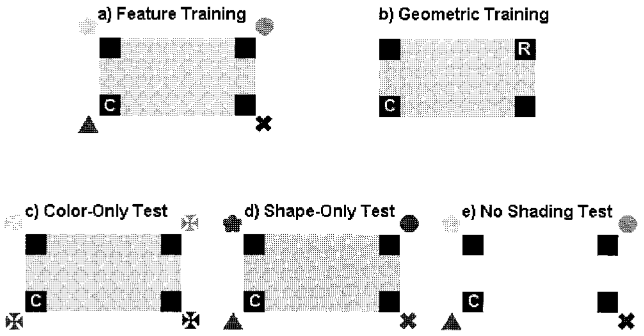

Figure 1. Examples of the images used in feature training (a), geometric training (b), Color-Only test (c), Shape-Only test (d), and No Shading test (e). The Move test is not shown here. For the purpose of illustration, all of these examples are drawn as if the red triangle was the feature in the correct corner (the "C" indicates the position of the correct corner, and the "R" indicates the geometrically correct corner, i.e., a systematic rotational error), although this was counterbalanced across participants.

Table 1
Design of Experiment 1

Group F–G				Group G–F			
Rotation 0°–180°	Rotation 45°–225°	Rotation 90°–270°	Rotation 135°–315°	Rotation 0°–180°	Rotation 45°–225°	Rotation 90°–270°	Rotation 135°–315°
Feature training Feature testing Geometric retraining Geometric testing				Geometric training Geometric testing Feature retraining Feature testing			

These instructions were developed so as not to include any reference to indicate that the images were representations of a spatial environment. Once the participants were given the instructions, the researcher started the experiment and waited outside of the room.

Each program began with a minimum of 12 training trials that presented each of the six training images two times. If the participant chose correctly on 80% of the trials he or she was moved on to testing; otherwise training continued, and accuracy was again calculated after each additional 12 trials (only the most recent 12 trials were used to calculate accuracy). When a participant made an incorrect choice he or she was re-presented with the same image until a correct choice was made. These additional choices were not used in the calculation of accuracy. This routine continued until the participant either met the accuracy criterion or had completed a total of 60 training trials. If the participant had not achieved 80% or greater accuracy by the completion of 60 trials, they were moved onto testing but their data were not used.

Once participants completed the first stage of testing they were retrained with the opposite condition (i.e., if they were in group F–G, they were retrained and tested with the geometric condition and, likewise, if they were in group G–F, they were retrained and tested with the feature condition). Once the participant completed the second testing phase (or 45 min had elapsed) the experiment ended.

The image set consisted of eight different rotations in which the rectangular environment differed by 45 degrees (i.e., 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°). Participants were divided into four subgroups that differed in which image rotations were presented during training and testing. Participants in subgroup 0°–180° were presented with all rotations except 0° and 180°, participants in subgroup 45°–225° were presented with all rotations except for 45° and 225°, and so on for subgroup 90°–270° and subgroup 135°–315°. (This procedure was adopted to examine performance on novel rotations in Experiment 2. Maintaining this procedure in Experiments 1 and 3 allowed us to more easily compare performance across all three experiments.)

Table 2
Summary of Experimental Testing Conditions for All Three Experiments

Experiment	Feature tests	Geometric tests
1	Feature Control Move No Shading Color-Only Shape-Only	Geometric Control Move No Shading
2	Feature Control Geometric Only Distant Affine Diagonal	Geometric Control New Rotation
3	Feature Control Distant Near Distant Far	

Training and Testing Procedures

Feature training. Six images showing a schematic of a rectangular environment were shown sequentially. In each image a distinctive feature was located at each corner of the rectangular environment. Each feature had a unique color and shape (see Figure 1A).

Feature testing. Testing was conducted in two phases. In Phase 1, participants were presented with three trial types: baseline trials, control trials, and two types of testing trials. During all baseline trials the same images as used in training were presented, and participants always received feedback as to whether their choice was correct or incorrect. Control trials presented the same images as used in baseline trials, but participants were never given feedback as to whether their choice was correct or incorrect. Test trials manipulated some aspect of the featural information provided in the images and were always presented without feedback.

In each phase of testing participants were randomly presented each baseline image six times, each control image two times, and each test image two times. Because only the baseline trials were reinforced, this provided participants with a 50% reinforcement schedule.

The two testing conditions presented in Phase 1 were the Color-Only test and the Shape-Only test (see Figure 1C). The Color-Only test presented the same rectangular environment as in training, but all features were presented in the shape of a formeé cross. The four identically shaped features were presented in the same distinct colors as in training. Therefore, this test examined whether the participants had encoded the distinct color of the features during training. If the participants encoded the shape but not the color of the features, they would not be able to determine which corner was correct. In the Shape-Only test, all features were an identical purple but maintained the same shape as during training. Therefore, this test examined whether the participants had encoded the shape of the features.

Phase 2 of testing immediately followed Phase 1 and included the Move test and the No Shading test (see Figure 1C). For both of these tests, all of the featural information remained identical to the training trials. For the Move test, rather than displaying the rectangular environment in the center of the screen, we presented the environment in the lower right-hand corner of the display. Thus, the Move test assessed whether participants learned the correct goal locations by simply memorizing the absolute location of the goal positions on the screen. For the No Shading test, the gray-shaded rectangle was removed to determine whether the continuous gray surface of the rectangle was an important aspect of the environment.

Geometric training. All general training procedures were identical to featural training, so only the exceptions are explained. Each participant was provided with six images depicting the same schematic of the rectangular environment as used in featural training. However, unlike featural training, none of the images contained any distinctive features (see Figure 1B). Therefore, the only source of information available to determine which corner was correct was the geometric information provided by the shape of the rectangle and/or the configuration of the four black squares. Because of the symmetry of the rectangular environment, it is impossible to distinguish the correct corner from the corner diagonally opposite to it. Therefore, in calculating accuracy, we counted responses to both the correct corner and the corner diagonally across from it (the geometrically equivalent corner) as correct.

Geometric testing. The testing procedures were very similar to those used in featural testing except for that none of the distinctive features were present and only one testing condition was presented per testing phase. The first phase included a Move test in which the images were presented in the lower right corner of the screen. The second phase included a No Shading test in which the light-gray shading was removed from the rectangle.

Data Analysis

All data presented are from the nonreinforced control and test trials. Only responses directed to the four black squares were counted. To determine how the participants were responding, we calculated the percentage of choices made to each corner (% choice) averaged over all the participants in the particular group. For all statistical tests, our criterion for significance was $p < .01$. Data analysis was carried out by analyses of variance (ANOVAs) for mixed-factor designs; subsequent Fisher's least-significant difference (LSD) tests were conducted only when significant F ratios were found. We conducted additional t tests to examine specific hypotheses about choices to one or two corners.

Results

In group F–G, 1 participant (a woman) failed to learn both the featural training and geometric retraining. Eight other participants (6 women and 2 men) failed to learn the geometric retraining, but all of these participants learned the initial feature training. In group G–F, 10 participants (9 women and 1 man) failed to learn the initial geometric training but subsequently learned the featural retraining. One participant (a man) failed to learn the featural retraining but learned the initial geometric training. If a participant failed to meet the training criterion, his or her data were not used for that particular condition.

Too few men participated in this study to allow for the examination of gender as a factor in any of the analyses. Although it might seem as though many more women failed to learn the geometric training procedures, the proportion of women (.57) and men (.5) who failed to learn geometry was similar.

Overall, more participants learned to use the featural information (93.8%) than learned to use the geometry (56.3%; McNemar's test $p < .01$). Therefore, although some participants were able to learn to use the geometric information, it was difficult.

Featural Testing

Data used in the following analyses are from a total of 15 participants from group F–G and 15 from group G–F. For all featural tests, we used a chance level of 50% (hereinafter referred to as geometric chance). This would be the expected accuracy if the participants encoded the geometric properties of the environment and chose randomly between these two geometrically equivalent corners, failing to use the features. For the Phase 1 tests, which manipulated properties of the features (Color-Only and Shape-Only tests), we considered choices to the corner containing the feature with the correct color (Color-Only tests) or the correct shape (Shape-Only tests) as a correct choice. A mixed-variable ANOVA, Group (F–G and G–F) × Trial Type (Feature Control, Color-Only, and Shape-Only tests), on accuracy scores showed no effect of group, $F(1, 28) = 2.09$, $p > .05$. However, a significant effect of trial type was found, $F(2, 56) = 8.04$, $p < .001$. A Fisher's LSD test showed that the average percentage of choices to the Feature Control test (96.5%) was significantly different from both the Color-Only (81.9%) and the Shape-Only (86.4%) tests (see Figure 2). The Color-Only and Shape-Only tests were not significantly different from each other. A one-sample t test showed that although the participants were on average less accurate at choosing the correct corner on the Color-Only and Shape-Only tests, they still chose this corner more often than geometric chance, 50%; $t(29) = 6.64$, $p < .0001$, $t(29) = 10.85$, $p < .0001$, for the Color-Only and Shape-Only tests, respectively.

For the Phase 2 tests, which manipulated the general environment but did not alter the four distinct features (i.e., Move test and No Shading test), we defined correct choices as choices to the featurally correct corner. A mixed-variable ANOVA, Group (F–G and G–F) × Trial Type (Feature Control, Move, and No Shading tests), on accuracy scores showed no effect of group, $F(1, 28) = 0.34$, $p > .05$, or trial type, $F(2, 56) = 1.79$, $p > .05$ (see Figure 3). This shows that participants continued choosing the correct corner when the entire rectangular environment was shifted from the center of the monitor's screen to the lower right corner or when the gray shading was removed.

Geometric Testing

Data used in the following analyses are from a total of 7 participants from group F–G and 6 from group G–F. A mixed-variable ANOVA, Group (F–G and G–F) × Trial Type (Geometric Control, Move, and No Shading tests), showed no significant effect of group, $F(1, 11) = 2.91$, $p > .05$, or trial type, $F(2, 22) = 2.39$, $p > .05$ (see Figure 4). To examine whether participants chose the two geometrically correct corners more often than expected by chance, we collapsed across the trial type and group factors and conducted a one-sample t test to compare choices of

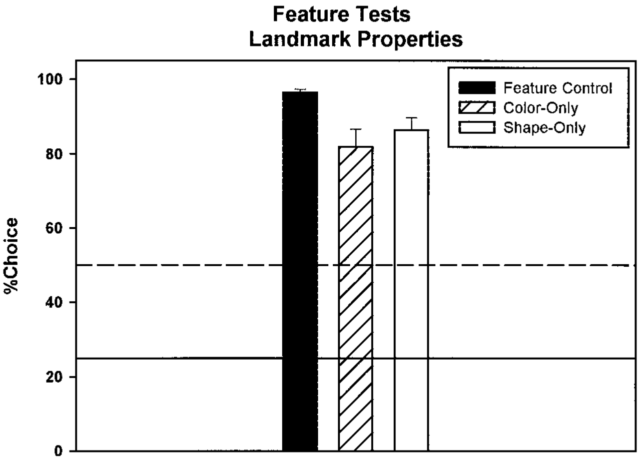

Figure 2. Percentage of choices to the correct corner by groups F–G and G–F for Feature Control tests, Color-Only tests, and Shape-Only tests. Error bars represent standard errors of the mean. The solid line indicates chance level if the participants had not encoded geometry; the dashed line indicates chance level if the participants had encoded geometry.

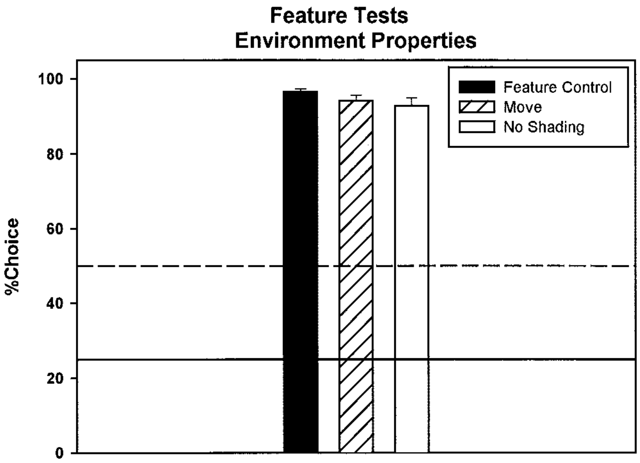

Figure 3. Percentage of choices to the correct corner by groups F–G and G–F for Feature Control tests, Move tests, and No Shading tests. Error bars represent standard errors of the mean. The solid line indicates chance level if the participants had not encoded geometry; the dashed line indicates chance level if participants had encoded geometry.

the two geometrically correct corners (88.5%) with chance (50%). The results of this analysis, $t(38) = 16.31$, $p < .0001$, showed that participants responded to the two geometrically equivalent corners more often than expected by chance, indicating that they had learned to use the geometric properties of the rectangular environment. Furthermore, a paired t test showed no differences between the positive corner and the geometrically equivalent corner, 41.8% and 46.7%, respectively; $t(38) = -1.18$, $p > .05$. The results from the No Shading test showed that the participants could use the geometric properties defined by the configuration of the four black squares and, thus, geometry did not have to be defined by a continuous surface.

Discussion

We found that participants were able to use the featural and geometric cues of the rectangular environment to locate the hidden goal. However, more participants were able to learn the featural task than the geometric task both after initial training and after retraining. Therefore, although possible, learning to use the geometry of a 2-D schematic environment was not easy. It is interesting that when using a 3-D model, in the task by Gouteux, Vauclair, and Thinus-Blanc (2001), adults readily used the geometric information when the featural cues were not present. However, in our task, several participants failed to learn to use the geometric information to solve the task. Although our procedure and the one used by Gouteux et al. differ in many ways, an interesting possibility is that geometric properties of an environment represented by only 2-D cues may be less salient and more difficult to encode. Perhaps this is especially so given the participants were not told that the images represented a spatial environment.

The participants showed strong control by the distinctive featural information, with many participants performing with perfect or near perfect accuracy during control trials with the featural information present. When we removed color or shape cues to examine which properties of the featural information controlled choices, we found that performance dropped but participants remained quite accurate at choosing the correct corner. Furthermore, the participants continued to use featural information even when the rectangular environment was shifted from the center of the screen or the gray shading was removed (i.e., Move and No Shading tests). Given that participants strongly relied on featural cues, it is perhaps not surprising that they continued to search on the basis of the featural information during the Move and No Shading tests.

More interesting, however, is our findings from the No Shading test with group G–F. After removal of the gray shading, in the No Shading test, the participants still showed strong geometrically guided responses. This shows that they were able to use the geometry of the configuration of the four discrete black patches, and thus, geometry did not need to be presented as a continuous surface. Gouteux and Spelke (2001) trained adults and children to locate a goal using the configuration of three or more landmarks in a circular environment. They also found that adults (but not children) were able to use the geometric properties of the configuration of landmarks to find a hidden goal (however, see Garrad-Cole, Lew, Bremner, & Whitaker, 2001, for contrasting results with children). This is similar to other studies examining the use of landmark configurations by adults (Spetch et al., 1996, 1997). Our study differs from previous ones in showing that adults could use the configuration of black squares even though this was not required to solve the training task. During training, participants could extract the geometric information from the continuous surface provided by the shading, so the geometric properties of the four discrete black patches need not have been encoded. Therefore, our results are interesting because they show that, even when trained with continuous geometry, adults are able to extract the geometric properties from a configuration of discrete objects.

Experiment 2

Previous experiments investigating the use of geometric and featural information by adults found that participants spontaneously encoded the geometric properties of the environment when

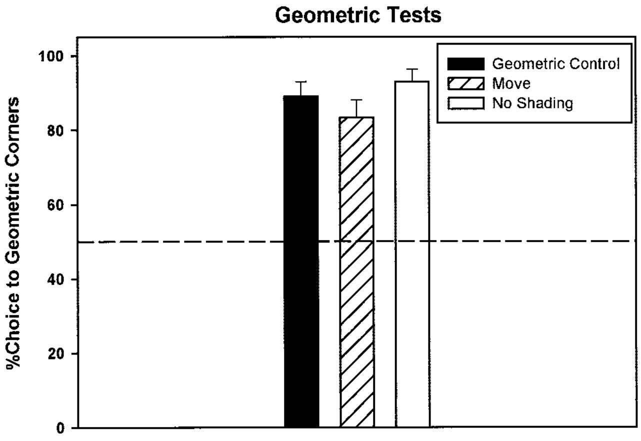

Figure 4. Percentage of choices to the two geometrically correct corners by groups F–G and G–F for geometric tests: Geometric Control, Move, and No Shading tests. Error bars represent standard errors of the mean. The dashed line indicates chance level if participants had encoded geometry.

only knowledge about the featural information was needed to solve the task (e.g., Hermer & Spelke, 1994, 1996). In Experiment 1, we specifically trained the participants to encode the geometry of the room by not presenting any distinctive featural cues (i.e., geometric training). Therefore, although we showed that the participants were able to encode the geometric properties of the environment, this was only after specific training to do so. In this second experiment, we examined whether participants would show similar spontaneous encoding of geometric information when discrete featural cues were present in addition to the geometric information (i.e., during featural training), as has been shown in 3-D environments. Given the difficultly many participants had in Experiment 1 in learning to use the geometry when specifically trained to do so, it seemed possible that featural cues would overshadow geometry when both sources of information were present during training.

In this second experiment, we also examined the flexibility of geometric encoding. Specifically, could the participants use the geometric information if the rectangular environment was presented in a novel rotation (one not seen during training)?

We also examined how many of the featural cues were encoded. The results of Experiment 1 showed that the participants' choices were strongly guided by the presence of featural information (i.e., color and shape), but it is unclear whether all four distinct featural cues were encoded. It is possible, for example, that participants learned only about the feature at the reinforced corner. Knowing how the participants encoded the featural information helps us to understand whether the participants used the array of features as landmarks or whether they simply used the feature associated with reinforcement as a type of beacon. Finally, we examined the interplay between geometric and featural cues. For example, if the featural and geometric cue(s) gave conflicting information about the location of the correct black square, which source of information would the participants use?

Method

Participants

Participants were 32 undergraduate students from the University of Alberta, Edmonton, Canada. Nineteen women and 13 men participated in the experiment to obtain credit for their introductory psychology course (ages ranged from 16 to 23 years and 17 to 31 years, respectively; average age = 19.8). As in Experiment 1, participants were randomly assigned to either group F–G (8 women and 8 men) or group G–F (11 women and 5 men), with the constraint that each group had to have an equal number of participants (16 participants per group). Once assigned to a group, each participant was also randomly assigned to one of four image-rotation subgroups (see explanation in Experiment 1 *General Procedures* section), again with the constraint that each image-rotation subgroup had to have an equal number of participants (4 participants per subgroup, counterbalanced for correct corner).

Design

The design of the experiment was identical to Experiment 1 with the exception of the testing conditions used in the feature tests and the geometric tests. The feature tests were: Feature Control, Geometry, Distant, Affine, and Diagonal. The geometric test was the New Rotation test.

Apparatus and General Procedures

The apparatus and instructions were identical to those used in Experiment 1.

Feature training. All training procedures and number of trials were identical to the feature training in Experiment 1.

Feature testing. Many of the testing procedures and number of trials were identical to the feature testing in Experiment 1; therefore, only the exceptions are described.

Phase 1 included the geometry test and the distant test. The geometry test presented the same rectangular environment with the four black squares, but all of the distinct featural information was removed (see Figure 5A). Thus, the only information available to the participants was the geometric information. The distant test was identical to training images except for that the featural information in the correct corner and the diagonally opposite corner was removed (see Figure 5B). Thus, to determine which corner was correct, the participants had to have encoded something about the features in one, or both, of the distant corners.

Phase 2 immediately followed completion of Phase 1. The two testing conditions used in Phase 2 were the Affine test and the Diagonal test (see Figure 5C and 5D, respectively). The Affine test is a transformation test that essentially moves each feature one position clockwise. Therefore, the configuration of the features is maintained, but the features that were in geometrically correct corners are moved to geometrically incorrect corners.

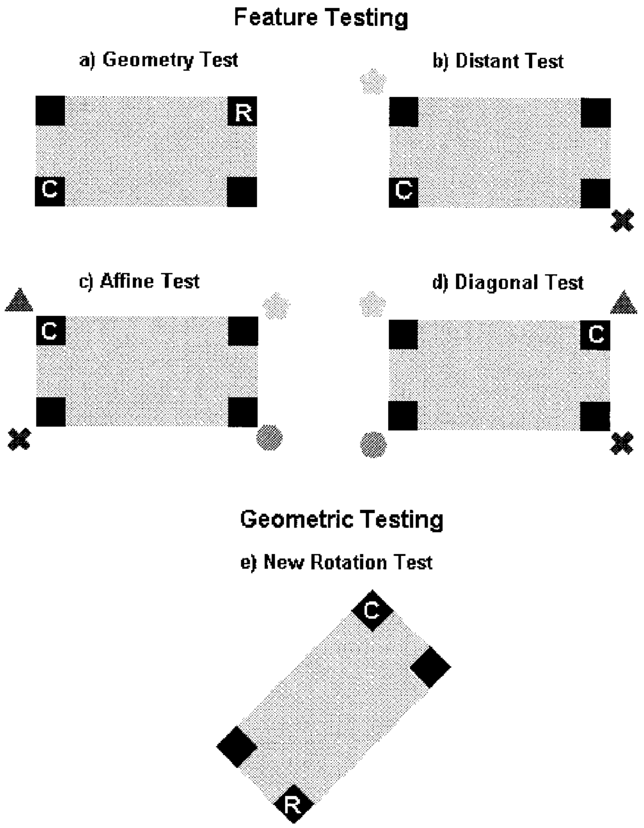

Figure 5. Examples of the images used in feature testing: Geometry test (a), Distant test (b), Affine test (c), and Diagonal test (d). Example of an image used in the geometric testing: New Rotation test (e). For the purpose of illustration, all of these examples are drawn as if the red triangle was the feature in the correct corner (the "C" indicates the position of the correct corner, and the "R" indicates the geometrically correct corner, i.e., a systematic rotational error).

The Affine transformation serves to pit featural information against geometric information. The second test in this phase was the Diagonal test. In this test, the correct feature and the feature diagonally opposite to it were switched. Therefore, the correct feature is still in a geometrically correct location but the configuration of the featural cues is altered.

Geometric training. All training procedures and number of trials were identical to the geometric training in Experiment 1.

Geometric testing. Many of the testing procedures and number of trials were identical to the geometric training in Experiment 1, and therefore, only the exceptions are described. Testing was conducted in a single phase and included a New Rotation test (see Figure 5E) in which participants were presented with the two novel rotations that they had not seen during training. For instance, the New Rotation test for subgroup 0°–180° showed the geometric environment at the two rotations of 0° and 180°. Each test image was presented a total of six times (thus, maintaining the 50% reinforcement schedule).

Results

One participant failed to learn both the geometric training and the featural retraining (a man). Eight other participants failed to learn the initial geometric training (5 women and 3 men) but subsequently learned the featural retraining. Nine participants failed to learn the geometric retraining (6 women and 3 men), but all of these participants learned the initial feature training. The test data for the unlearned condition were not used in any of the analyses.

Too few men participated in this experiment to allow for the examination of gender as a factor in any of the following analyses. The proportion of women (.58) and men (.54) who failed to learn geometry was similar.

Overall, more participants learned to use the featural information (96.9%) than learned to use the geometry (43.8%; McNemar's test $p < .01$). Therefore, although some participants were able to learn to use the geometric information, it was again a very difficult task.

Feature Testing

Data used in the following analyses are from a total of 16 participants from group F–G and 15 participants from group G–F. To examine the effects of the transformation tests, we compared choices to the featurally correct corner across all test types. A mixed-variable ANOVA, Group (F–G and G–F) × Trial Type (Control, Affine, Diagonal, and Distant tests), showed no main effect of group, $F(1, 29) = 0.14$, $p > .05$. However, a significant main effect of trial type was found, $F(3, 87) = 58.35$, $p < .0001$. A Fisher's LSD test showed that the percentages of choices to the correct feature on the Control test (98.4%), the Diagonal test (95.7%), and the Affine test (93.5%) were all significantly different from the Distant test (62.6%; see Figure 6).

When learning which corner was correct, participants could have learned only about the feature in the correct corner or something about several features. If they encoded only the feature in the correct corner, then on Distant tests they would be able to eliminate the corners with the incorrect features but would have no basis for choosing between the two corners containing no featural information. Consequently, we expected participants to choose randomly between these two corners. On the other hand, if participants encoded information about the distant features, they should be able to use this distant information to choose the correct corner more often than expected by chance. A one-sample *t* test showed that the participants chose the correct corner significantly more often (62.6%) than expected by chance (50%), $t(30) = -3.59$, $p < .01$. This result shows that even though participants were less accurate in choosing the correct corner when only the distant information was provided, they must have encoded enough of the distant featural cues to allow them to choose the correct corner more often than would be expected if they randomly chose between the two geometrically correct corners.

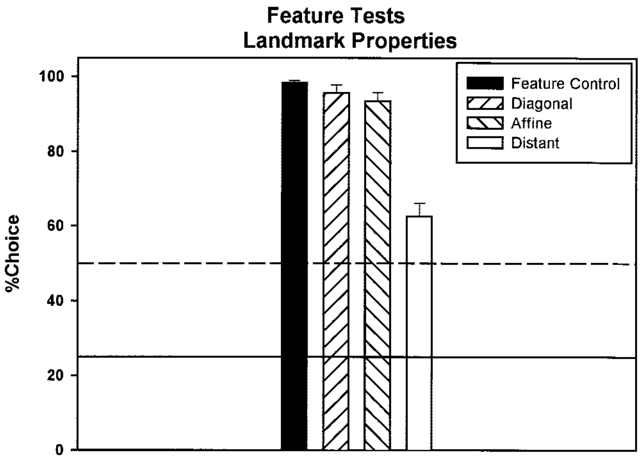

Figure 6. Percentage of choices to the correct corner by groups F–G and G–F for feature tests: Feature Control, Diagonal, Affine, and Distant tests. Error bars represent standard errors of the mean. The solid line indicates chance level if the participants had not encoded geometry; the dashed line indicates chance level if the participants had encoded geometry.

Did group F–G encode the geometric properties of the rectangle (or the configuration of the four black squares) even though this was not necessary to learn the task? The Geometry test allowed us to examine this possibility. If the participants encoded the geometric properties, we expected that when we removed all the featural cues the participants would respond primarily to the two geometrically correct corners. To determine whether this was the case, we compared the percentage of total choices made to the two geometrically correct corners (65.1%) to chance level response of 50% using a one-sample *t* test, $t(15) = 3.13$, $p < .01$ (see Figure 7). A paired *t* test showed no differences between the positive corner and the geometrically equivalent corner (32.3% and 32.8%, respectively), $t(15) = -0.17$, $p > .05$. These result show that participants spontaneously encoded the geometric properties of the environment even though such encoding was not required.

Geometric Testing

Data used in the following analyses are from 7 participants from group F–G and 7 participants from group G–F. A mixed-variable ANOVA, Group (F–G and G–F) × Trial Type (Control and New Rotation tests), showed no main effect of group, $F(1, 12) = 1.67$, $p > .05$. However, a significant main effect of trial type was found, $F(1, 12) = 10.13$, $p < .01$. A Fisher's LSD test showed that the average percentage of responses directed to the two geometrically correct corners was significantly larger on the Control test (87.5%) than on the New Rotation test (60.7%; see Figure 8). One-sample

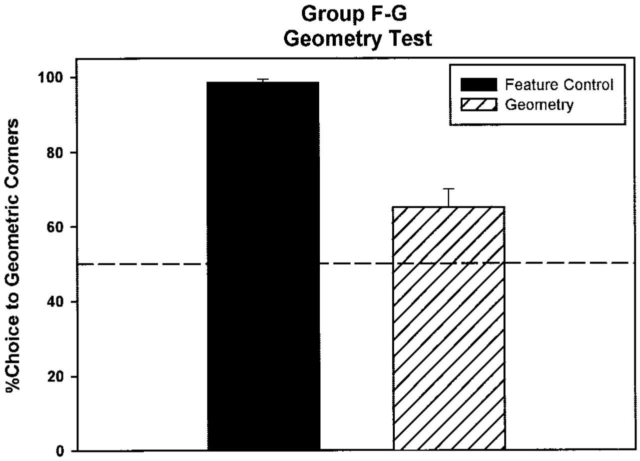

Figure 7. Percentage of choices to the two geometrically correct corners by group F–G for the Feature Control and the Geometry tests. Error bars represent standard errors of the mean. The dashed line indicates chance level if the participants had encoded geometry.

t test showed that on the New Rotation test the participants did not choose the two geometrically correct corners more often than would be expected by chance (50%), $t(13) = 1.41$, $p > .05$. Choices to the two geometrically correct corners were, however, distributed evenly (29.7% and 31.0% to the positive and geometrically equivalent corners, respectively), $t(13) = -0.29$, $p > .05$.

Discussion

As in Experiment 1, we found that the participants readily learned to use the featural information to locate the correct corner. Again, several participants failed to learn to use the geometry of the rectangular environment to solve the geometric task. Examining the results from the feature tests, we found that participants followed the correct feature even when it was placed in a geometrically incorrect corner (i.e., the Affine test) or when the order of featural cues was disrupted (i.e., the Diagonal test). Interestingly, when we removed the featural information in the two geometrically correct corners, leaving only the distant cues (i.e., Distant test), we found that although the participants chose the correct corner significantly less often than on control trials, they were significantly more accurate than chance. This indicates that the participants encoded the featural information in the distant corners but used this information to a lesser degree than the featural information in one or both of the geometrically correct corners.

Although many participants in Experiments 1 and 2 failed to learn to use the geometric information to solve the task, when we tested group F–G with all distinctive featural information removed (i.e., Geometry test), we found that the participants showed systematic rotational errors, indicating that they had encoded the geometric properties of the rectangular environment even though this was not necessary to solve the task during feature training. This result supports and extends previous studies showing that encoding of geometric information is not overshadowed by the featural cues (e.g., Hayward, McGregor, Good, & Pearce, 2003; Kelly et al., 1998; Vallortigara et al., 1990). Previous studies have shown that several animals, including humans, will readily encode the geometric properties of a 3-D environment (e.g., humans: Hermer & Spelke, 1994, 1996; birds: Kelly et al., 1998; Vallortigara et al., 1990; and fish: Sovrano et al., 2002). The results from the Geometry test show that even in a very spatially limited schematic of an environment, and even when participants are not informed that the schematic represented a spatial environment, the geometric properties of the environment are encoded. Moreover, this encoding of geometry is robust and resistant to overshadowing by the distinct featural information.

Two results support our conclusion that participants had encoded the geometric properties of our environment. The first is the finding that group F–G showed systematic rotational errors in the Geometry test. The second piece of evidence comes from the fact that in both Experiments 1 and 2 some participants learned to use the geometric properties of the rectangle to solve the task. However, our results from the New Rotation test suggest that participant's encoding of geometry was quite limited. When we changed the orientation of the environment, participants did not continue to use the geometric properties to distribute their choices between the two geometrically correct corners. Rather, the participants randomly chose among all four corners. This indicates that although participants were able to encode the geometry and did so spontaneously after being trained to use the featural information, the encoding of the geometric properties was orientation and sense specific.

Experiment 3

The results from the Distant test of Experiment 2 showed that the participants could use the featural information in the two nongeometrically correct corners to correctly find the goal. In this third experiment, we specifically examined how many of the distant features were used. For example, did the participants encode only the distant feature that was closest to the correct corner, or did they encode both distant features? By removing all of the featural cues except one, either the feature closest to the correct corner or the one farthest from the correct corner, we examined

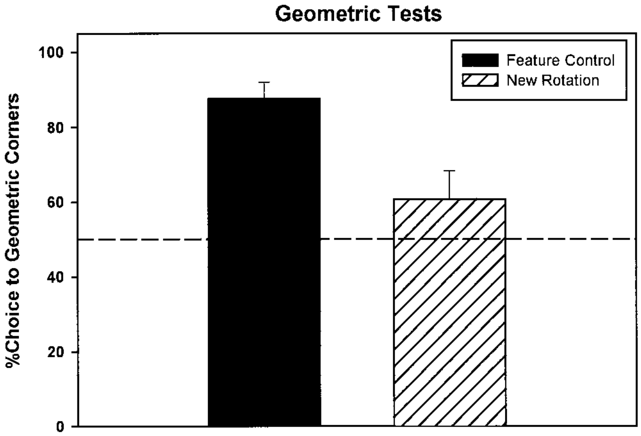

Figure 8. Percentage of choices to the two geometrically correct corners by groups F–G and G–F for geometric tests: Feature Control and New Rotation tests. Error bars represent standard errors of the mean. The dashed line indicates chance level if the participants had encoded geometry.

whether the participants learned about all of the distant featural information equally.

Method

Participants

The participants were 16 undergraduate students from the University of Alberta, Edmonton, Canada. Eleven women and 5 men (ages ranged from 19 to 41 years and 20 to 24 years, respectively; average age = 23.0) participated in the experiment to obtain credit for their introductory psychology course. Participants were assigned to the four rotation groups and to correct corners, as in previous experiments.

Design

The design of the experiment was a mixed-factor design (see Table 1). The between-subjects factor was Image Rotation (four levels: 0°–180°, 45°–225°, 90°–270°, and 135°–315°). The participants were trained with the same feature condition as in Experiments 1 and 2, and then received the following tests: Feature Control, Distant Near, and Distant Far.

Apparatus and General Procedures

The apparatus and instructions were identical to those used in Experiments 1 and 2.

Training

The training procedures were identical to those used in Experiments 1 and 2 for Feature training.

Testing

Most of the testing procedures used in this experiment were identical to those used in Experiments 1 and 2 for feature testing, so only the exceptions are discussed. Testing was conducted in a single phase. The two testing conditions were the Distant Near test and the Distant Far test.

For the Distant Near test, the featural information was removed in the two geometrically correct corners and in the corner farthest from the correct one. This left only the featural information in the corner nearest to the correct corner along the short wall (see Figure 9B). For the Distant Far test, the featural information was removed from the two geometrically correct corners and the corner closest to the correct corner. The feature in the corner along the long wall remained (see Figure 9C).

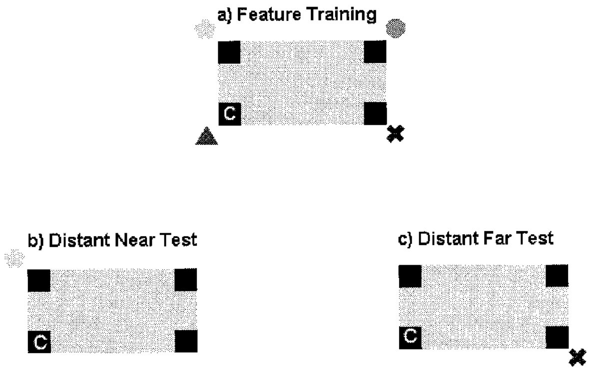

Figure 9. Examples of the images used in testing: Feature Control (a), Distant Near test (b), and Distant Far test (c). For the purpose of illustration, all of these examples are drawn as if the red triangle was the feature in the correct corner ("C" indicates the correct corner).

Results

All participants learned the task; therefore, the analyses included the data from all 16 participants. To examine the effects of the transformation tests, we compared choices to the corner that would be considered featurally correct according to the configuration of features (e.g., on the Distant tests the remaining feature is sufficient to indicate which corner should contain the correct feature). A repeated measures ANOVA, Gender (male and female) × Trial Type (Control, Distant Near, and Distant Far), showed no effect of gender, $F(1, 14) = 0.19$, $p > .05$. However, a significant effect of trial type was found, $F(2, 28) = 23.73$, $p < .0001$. A Fisher's LSD test showed that the average percentage of choices to the correct corner on Control tests (100.0%) was significantly different from both the Distant Near (88.5%) and the Distant Far (75.5%) tests (see Figure 10). Furthermore, the Distant Near test and Distant Far tests were significantly different from each other. Although both the Distant Near and the Distant Far tests were significantly different from the Control test, choices to the correct corner were significantly greater than would be expected by chance responding (50%), one-sample $t(15) = 14.7$, and $t(15) = 5.6$, $p\text{s} < .0001$, for the Distant Near and the Distant Far tests, respectively.

Discussion

As in Experiments 1 and 2, the participants quickly and accurately learned to use the featural information to choose the single correct corner. Accuracy decreased but remained above chance when we removed the featural information in the two geometrically correct corners and in one of the two distant corners. Participants were more accurate when the feature closest to the correct corner remained (the near feature) than they were when the feature farthest to the correct corner remained (the far feature). This result is consistent with previous investigations examining 2-D landmark use by adult humans, showing that landmarks farther from the goal may be overshadowed by landmarks closer to the goal (e.g., Spetch, 1995). Interestingly, accuracy was somewhat higher in this experiment than it was in the distant test of Experiment 2. We suspect that this difference reflects the fact that participants in Experiment 2 were presented with more testing conditions.

General Discussion

The purpose of our experiments was to examine how adult humans use geometric and featural information when this information is represented in a 2-D environmental schematic. We found that the adults encoded both the featural and geometric properties of the rectangular environment. In encoding the featural information, participants used both the distinctive colors and shapes of the featural cues (Experiment 1, Color-Only and Shape-Only tests), and when unable to use the feature directly associated with the correct corner, participants used distant features (with closer cues allowing for more accurate choices; Experiments 2 and 3, Distant, Distant Near, and Distant Far tests). We also found that although *learning* to encode the geometric properties of the environment was a difficult task, participants trained with featural information spontaneously encoded the geometric properties of the environ-

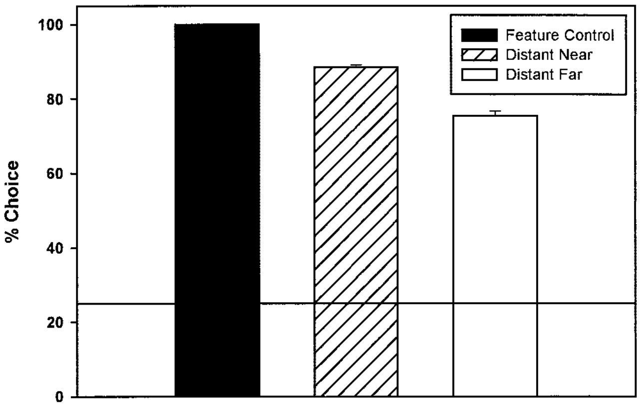

Figure 10. Percentage of choices to the correct corner for Feature Control, Distant Near, and Distant Far tests. Error bars represent standard errors of the mean. The solid line indicates chance level if the participants had not encoded geometry.

ment (i.e., results from group F–G during the geometric test in Experiment 2). However, manipulations of the geometric properties showed that this geometric encoding was sense and orientation specific (Experiment 2, New Rotation test). Finally, when featural and geometric information were put into conflict, participants showed extremely strong control by the featural information (Experiment 2, Affine test).

Previous experiments investigating the conjoining of geometric and featural cues have mainly concentrated on navigational tasks in which the participant actively locomotes through the environment (e.g., Hermer & Spelke, 1994, 1996; Hermer-Vazquez et al., 1999). However, the recent study by Gouteux, Vauclair, and Thinus-Blanc (2001) that used a model environment, although showing differences in developmental aspects of encoding, showed remarkable similarities to previous studies using a navigable environment. Our experiments further examined how environmental properties are encoded when participants view rather than navigate through a rectangular environment. Because many studies of human navigation make use of models or maplike representations of space, it is important to determine whether environmental information, such as the geometric properties, are used similarly in 2-D environmental representations and navigable environments. Some of our results are remarkably similar to those found with 3-D environments. For example, our participants were able to conjoin geometric and featural information, a result that replicates findings from several studies that used navigable environments. Previous comparisons of landmark use in 2-D and 3-D environments have also shown many similarities in how adults use featural information, suggesting that 2-D tasks are useful for examining cognitive processing of spatial information, even though they differ markedly from real-space environments (Spetch et al., 1996, 1997).

Our findings show that geometry was encoded using orientation- and sense-specific Euclidean properties. This type of encoding supports our consistent finding that learning to use only the geometric information was a difficult task (i.e., geometric condition). Encoding the geometric properties using an orientation- and sense-specific strategy requires that the participants use three separate codes, one for each unique training orientation. For example, participants in the 0°–180° subgroup would need one code for rotations 45° and 225°, a second code for rotations 90° and 270°, and a third code for rotations 135° and 315°. Therefore, this type of encoding would explain the relative difficulty of learning the geometric condition in comparison to the feature condition and accounts for the participants' failure to use geometry during the New Rotation test. Nevertheless, the finding that participants in group F–G spontaneously encoded geometry during their training with features indicates that the encoding of features and geometry proceeds in parallel and independently. Learning the easier code provided by features did not interfere with learning the more difficult multiple codes for the geometry.

What might cause this orientation-specific encoding of geometry in our task? One notable aspect of our experimental procedure that differs from several previous studies examining the use of geometry is that our rectangular arena was located within a larger, directionally stable search space. In most previous studies on geometric encoding, the arena is an enclosed environment, so that directional information from the external world is blocked, and internal directional cues are often disrupted by rotating the participant. Furthermore, our 2-D arena was presented on a vertically oriented computer screen, which likely provided a highly salient directional frame of reference. The orientation of the arena on the screen differed across trials, and participants were not able to witness the orientation change. Moreover, the vertical axis provided by the computer screen may represent a gravity-defined privileged axis. Such privileged axes have been reported in horizontal tasks with insects (e.g., bees, Cartwright & Collett, 1982; ants, Rossel & Wehner, 1986). Presenting our rectangular arena against a stable external world, likely with a privileged axis of space, may have encouraged orientation-specific encoding of geometric information (also see Friedman & Hall, 1996).

The present findings raise interesting questions that suggest several lines of future research. First, did the orientation specificity of geometric encoding occur because of the use of a privileged vertical axis? In future investigations, it would be interesting to explore the potential influence of privileged axes by presenting the environments on a horizontal monitor with a circular screen. Such a manipulation should remove the privileged axes biases and may be less likely to encourage orientation-dependent encoding. Gouteux, Vauclair, and Thinus-Blanc (2001) rotated their model environment across trials on a horizontal surface, but unfortunately, they did not include tests to assess the influence of orientation on geometric encoding.

Second, to what extent would the results found here with humans generalize to other species? In real 3-D environments, several species have been shown to conjoin geometric and featural information (e.g., fish, Sovrano, Bisazza & Vallortigara, 2002; chicks, Vallortigara, Zanforlin & Pasti; pigeons, Kelly, Spetch & Hethal, 1998; cotton-top tamarins, in a modified procedure, Deipolyi, Santos, & Hauser, 2001; larger cues, rhesus monkeys, Gouteux, Thinus-Blanc, & Vauclair, 2001). Some species have been found to rely on both the color and shape of featural cues (e.g., pigeons, Kelly et al., 1998; cotton-top tamarins, Deipolyi et al., 2001). Interestingly, from the nonhuman species thus far tested (i.e., rats, chicks, pigeons, and rhesus monkeys), only the pigeons have been shown to use the distant featural properties to locate the hidden goal (however, for rhesus monkeys this may have been a factor of the size of the features; Experiment 4, Gouteux, Vauclair, & Thinus-Blanc, 2001). Whether any or all of these findings with animals would hold within a 2-D environment is not known. Adult humans have extensive experience in interpreting maplike representations of real environments, whereas animals presumably do not. Nevertheless, studies of landmark use have revealed surprising correspondence between spatial encoding processes in 2-D and 3-D tasks (Spetch et al., 1996, 1997).

A third line of future research needs to address questions that remain regarding the encoding of geometric information in maplike representations by humans. For example, results from studies with pigeons and chicks suggest that the surface geometry can be encoded in terms of relative metrics or a strategy including both relative and absolute metrics (Gray, Spetch, Kelly, & Nguyen, in press; Kelly & Spetch, 2001; Tommasi & Vallortigara, 2000; Tommasi, Vallortigara, & Zanforlin, 1997). Is encoding of 2-D geometry by humans based on absolute or relative metrics? Does the encoding of geometry and features show the same developmental pattern as seen with real or model environments? Is the size of the maplike representation a factor in the developmental sequence of geometric and featural coding as it is in 3-D environments (Learmonth et al., 2002, also see Newcombe & Huttenlocher, 2000)? Would encoding of geometry in a maplike environment be enhanced by the opportunity to view rotations of the environment (Brodbeck, Pike, & Spracklin, 2003) or by specifically instructing participants that the 2-D images depict a representation of a 3-D environmental space? Furthermore, it would be interesting to examine whether the encoding of environmental geometry is influenced when the rectangular environment is presented from side views as well as top views, as in a virtual environment (Kelly & Bischof, 2002). Given that humans extensively use maps of both artificial and natural environments to derive or communicate spatial information, it is important to understand the nature and extent of geometric encoding in maplike representations.

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