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Reorienting in Images of a Three-Dimensional Environment

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Adult humans searched for a hidden goal in images depicting 3-dimensional rooms. Images contained either featural cues, geometric cues, or both, which could be used to determine the correct location of the goal. In Experiment 1, participants learned to use featural and geometric information equally well. However, men and women showed significant differences in their use of distant featural cues and the spontaneous encoding of geometric information when trained with features present. Transformation tests showed that participants could use either the color or the shape of the features independently to locate the goal. Experiment 2 showed that participants could use either configural or surface geometry when searching for the goal. However, their weighing of these geometric cues was dependent on initial training experience.

Keywords: human, feature, geometry, configuration, surface

Many important and reliable cues can be found within an environment that allow an animal to orient and subsequently to navigate. In general, these cues may be categorized into two main types, geometric cues and featural cues (also referred to as *nongeometric cues*). Gallistel (1990) provided a clear definition of these cues:

> A geometric property of a surface, line, or a point is a property it possesses by virtue of its position relative to other surfaces, lines, and points within the same space. A nongeometric property is any property that cannot be described by relative geometry alone. Any property whose description requires language that does not ordinarily appear in a textbook on geometry is nongeometric. (p. 212)

Whether human and nonhuman animals can conjoin geometric and featural properties has been a topic of considerable interest, which is demonstrated by the wealth of research it has sparked recently. The use of featural and geometric cues for reorienting in a rectangular environment has been examined with a variety of species and with several different tasks (e.g., fish; Sovrano, Bisazza, & Vallortigara, 2002, 2003; rats; Margules & Gallistel, 1988; pigeons; Kelly & Spetch, 2004b; Kelly, Spetch, & Heth, 1998; chicks; Vallortigara, Zanforlin, & Pasti, 1990; rhesus monkeys; Gouteux, Thinus-Blanc, & Vauclair, 2001; human children; Gouteux, Vauclair, & Thinus-Blanc, 2001; Hermer & Spelke, 1994, 1996; and adults; Kelly & Spetch, 2004a).

Pioneer experiments by Cheng (1986) showed that although geometric cues were weighed more heavily than featural cues, rats were able to use both types of information to find a goal location in a fully enclosed rectangular environment. In one of the experiments in the study, Cheng trained disoriented rats on a reference memory task to locate food hidden in one corner of the environment. The orientation of the enclosure within the larger experimental room varied across trials to ensure that the rats would not be able to use any extraenvironmental cues. Four very distinct featural cues were placed in the enclosure, one in each corner. In front of these featural cues was a glass bottle. Only one glass bottle consistently contained a food reward; this bottle was always associated with a particular featural cue, but the cue was counterbalanced across subjects. A rat was placed in the enclosure and allowed to search until it knocked over the bottle containing food. Training continued until each subject chose the correct bottle first on 9 out of 10 consecutive trials. It is interesting that although the rats were able to learn this task, they made many errors. These errors were not randomly distributed among the four corners of the enclosure: The rats showed *systematic rotational errors* in that they frequently chose the bottle in the corner diagonally opposite to the correct corner. These errors show that although the rats were able to use the featural cues, they strongly relied on the geometric properties of the environment.

Studies with human participants have indicated that young infants also may show strong control by the geometric properties of the environment. Hermer and Spelke (1994) used a similar experimental paradigm to examine whether human adults and children were able to use the geometric and featural properties in a rectangular environment to locate a desired target location. While the children watched, an experimenter hid a small preferred toy in the corner of the rectangular room. The children then closed their eyes

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and were rotated to rid the use of an inertial sense of direction. They were then asked to open their eyes and locate the hidden toy. The children showed similar errors to those of the rats in Cheng's (1986) experiments: They searched not only at the correct corner but also equally often at the corner diagonally opposite to where the hidden toy was located. Adults did not show these systematic rotational errors when searching in a similar task but were very accurate at locating the position of the hidden object. The experimenters concluded that young children must have a *geometric module* similar to that found in rats. This modular organization of spatial information encodes only the geometric properties of the shape of the environment. The researchers further suggested that this geometric module could be overridden with development to allow for the conjoining of geometric and featural information.

Following these initial investigations into the geometric module and the conjoining of geometric and featural information for reorientation, many studies have further examined issues such as linguistic development or the scale of the search space to understand how featural information is overlaid on the geometric properties (e.g., Hermer-Vazquez, 1997; Hermer-Vazquez, Moffet, & Munkholm, 2001; Hermer-Vazquez, Spelke, & Katsnelson, 1999; Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, & Huttenlocher, 2001). The requirement of linguistic skills for such conjoining has been called into question by many studies showing conjoining of geometric and featural cues in nonlinguistic species (e.g., fish; Sovrano et al., 2002, 2003; pigeons; Kelly & Spetch, 2004b; Kelly et al., 1998; chicks; Vallortigara et al., 1990; and rhesus monkeys; Gouteux, Thinus-Blanc, & Vauclair, 2001).

The results reported from many studies investigating the use of spatial information for navigation illustrate the importance of search space in different types of spatial tasks (e.g., real-world navigational tasks; McNamara, Rump, & Werner, 2003; Richardson, Montello, & Hegarty, 1999; immersive virtual reality tasks; Astur, Ortiz, & Sutherland, 1998; Waller, Loomis, Golledge, & Beall, 2002; nonimmersive virtual reality tasks or 3-D images; Bischof & Boulanger, 2004; Ekstrom et al., 2003; Richardson et al., 1999; Sandstrom, Kaufman, & Huettel, 1998; or 2-D mapping tasks; Richardson et al., 1999; Saucier, Bowman, & Elias, 2003). Yet, until recently, few studies have examined the influence of scale and the nature of the spatial environment on the conjoining of geometric and featural cues for reorienting in an enclosed rectangular environment by adults (see Learmonth et al., 2001, for an interesting examination of how search space influences cue use by children). Gouteux, Vauclair, and Thinus-Blanc (2001) examined the encoding of geometric and featural cues by young children and adults using a model of a 3-D search space rather than a navigable space. Participants were seated in front of the model environment and watched an experimenter hide a target item in one corner. The model was then rotated while the participants kept their eyes closed. The participants were then asked to open their eyes and relocate the hidden object. The investigators found results in this model environment that were comparable to those other researchers had reported in navigable environments, although these abilities appeared to emerge slightly later in development.

Hartley, Trinkler, and Burgess (2004) examined how adults used geometric information in a nonimmersive virtual reality task. Participants were presented with a target object in a rectangular environment open to distant visual landmarks. After participants viewed the scene, they were presented with a brief delay and subsequently returned to the environment, with the target removed, but now facing a novel orientation. Participants were asked to indicate the position of the missing object. Using a series of environmental transformation tests, the authors found that the participants had encoded the geometric information supplied by the shape and size of the training environment and that this information was used in conjunction with orientational cues provided by distant landmarks.

Kelly and Spetch (2004a) further examined how adults use featural and geometric properties in images of a rectangular environment. In their study, participants were presented with images of a 2-D overhead view of a rectangular environment void of any relevant distant featural cues. Adults were trained to find and touch a hidden goal that was consistently located in one corner of the environment. Once the participants touched the goal location, they received feedback, and then another image of the environment from a new orientation was shown. The researchers found that, even in this simple environment, participants showed conjoining of geometric and featural cues. This study further provided an understanding of how geometry was being encoded.

Studies such as the ones discussed above further our understanding of how spatial cues are encoded in nonnavigable environments. However, both the Learmonth et al. (2001) and the Hartley et al. (2004) studies provided participants with distant landmark information. This information either had to be ignored (Learmonth et al.) or could be used for the purpose of reorientation (Hartley et al.). These differences in task requirements make conditions in these studies quite different from the fully enclosed rectangular environment typically used in navigable versions of this reorientation task. It is thus not clear whether these aspects influenced how the participants used the available information when establishing the target location. Indeed, as Hartley et al. discussed, their participants used the distant landmarks as an orientational cue. In our current study, we examine how adults use featural and geometric cues in 3-D images of a fully enclosed rectangular environment. This type of environment allows us to examine questions that would be difficult to address in a navigable environment while still permitting us to limit the cues available to only those within the environment (or from the structure of the environment itself).

We examine four main topics: (a) the relation between the use of featural and geometric cues when a subset of these cues was unavailable or provided conflicting information as to the location of the goal, (b) the encoding of featural properties and the influence of featural cue availability on the use of geometric information, (c) the encoding of geometric information supplied by the surfaces of the environment and by the configuration of discrete objects, and (d) sex differences in the encoding of spatial information in a reorientation task, for comparison with trends reported for navigational tasks. In investigating these central issues, we further the understanding of how adults use featural and geometric cues in a 3-D environment.

Experiment 1

In the first experiment, we examined whether adults could use the geometric and featural cues presented in images depicting a 3-D room. To investigate how participants were using the featural cues, we specifically examined what properties of the featural cues were encoded and whether a subset of the features could be used reliably. Previous literature has shown that when adults are trained with a similar task using 2-D images of a rectangular room and tested with either the shape or the color information removed, they show quite good transfer of responding (Kelly & Spetch, 2004a). Furthermore, when examining how adults use a subset of featural cues, Kelly and Spetch found that a single feature near the goal could be used more accurately than a single feature more distant from the goal in determining the goal location. However, the relative encoding of featural properties has not been examined using more realistic 3-D images. In our study, we examined whether men and women would show a similar decrement of performance when only one distant cue was available to determine the position of the goal area. Previous research using navigable environments led us to hypothesize that men would show less degradation in performance with only a single distant cue in comparison with women.

To investigate how participants were using geometric cues, we examined how geometry was encoded (i.e., using relative or absolute metrics) and whether it was encoded in terms of surface geometry (i.e., using geometric information supplied by the surfaces of the environment) or by configural geometry (i.e., using geometric information supplied by the configuration of discrete objects). Previous studies have shown that adults encode geometric information from 2-D schematic images of a rectangular environment (Kelly & Spetch, 2004a). Kelly and Spetch showed that participants made geometrically guided choices even when the gray background, which provided surface information, was removed. This suggests that participants were able to use the geometric information from the configuration of the discrete black response patches. In our experiment, we further examined the use of geometric properties to guide search behavior by manipulating the size of the configuration of the black response patches to examine whether the participants were using a relative or absolute encoding metric. On the basis of the fact that adults readily transfer information about pictures of real environments to the actual environment and vice versa, we hypothesized that the adults in our study should encode the configuration of objects using a relative metric.

Furthermore, we examined whether the encoding of geometry would be overshadowed when participants were initially trained with distinctive features present. Although studies with young children have shown that, in 3-D navigable environments, the learning of features is overshadowed by geometric information, featural and geometric cues do not seem to compete when adults are encoding the properties of a similar environment. In our study, we hypothesized that, similar to the encoding of navigable space, we would not find evidence of overshadowing. Finally, we examined the relative weighing of geometric and featural cues when these information sources provided conflicting information as to the correct location of the goal area. Many studies have shown that women and men use spatial information differently; thus, by pitting featural information against geometric information, we were able to examine possible sex differences in this environment. In particular, we were interested in the hypothesis generated from navigational studies that men but not women would show an encoding of geometric information.

Method

Participants

The participants were 32 students from the University of Nebraska—Lincoln and the University of Alberta, Edmonton, Alberta, Canada. Sixteen women and 16 men (with ages ranging from 19 to 25 years and 18 to 36 years, respectively, with an average age of 20.9 for both sexes) participated in the experiment.

Apparatus

Participants sat on a chair in front of a laptop computer monitor (Sony Vaio Notebook). All responses were made with a mouse, both for making choices and for proceeding to the next trial.

Images

The images were created via POV-Ray (2002) and showed a rectangular room with a granite floor and brick walls (see Figure 1a). On the floor, there were four identical black response patches, located near the corners of the room, and up to four objects (columns with a unique color and shape) were presented adjacent to the response patches. The number and properties of objects varied with training and testing conditions and are explained in more detail in the *Training and Testing Procedures* section. The room was seen from an elevated viewpoint in one of the corners or the middle of the walls; hence, eight different views were created for each room. The camera was directed at the center of the floor, with camera height and angle chosen such that every image showed (at least a part of) all walls and all

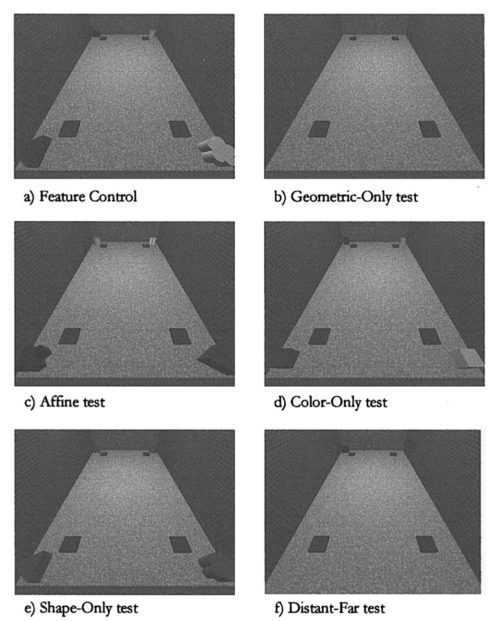

Figure 1. Examples of the images used in feature testing: (a) feature control, (b) geometric only, (c) affine, (d) color only, (e) shape only, and (f) distant–far. The feature control image shows an object in each of the corners—namely, a red triangle, a blue cross, a green cylinder, and a yellow flower-shaped block, in clockwise order. The distant–far image shows a single object along the long wall away from the correct response patch, which in this case would be in front of the red triangle. All of these examples are illustrated from the same viewpoint to show the test manipulations.

objects in the room. The images were generated with a resolution of 896 × 672 pixels, and they subtended a visual angle of 35.0° × 27.6° at the viewing distance of 40 cm.

Design

The design of the experiment was a mixed-factor design (see Table 1). The between-subjects factor was the training order: Participants were separated into the *feature–geometry group* (Group F-G) and the *geometry–feature group* (Group G-F). Participants were randomly assigned to either Group F-G or Group G-F, with the constraint that both groups had 16 men and 16 women. The participants in Group F-G were first trained with the feature condition and then tested with the following tests: feature control, geometry only, affine, color only, shape only, and distant–far. Then they were retrained with the geometry condition and tested with the following tests: geometric control, small, medium, square, and small rotated. For the participants in Group G-F, the order of the two training and test conditions was reversed. The specific details of the training and testing conditions are explained in the appropriate *Procedures* section.

General Procedures

The participants were trained and tested individually. Once seated in front of the computer monitor, participants were told that they would see a series of images presented one at a time. In these images, they would always see four black response patches. Their task was to determine which response patch was correct and to use the mouse to click on that patch. Once they clicked on a response patch, the image disappeared, and a screen appeared indicating that (a) they had chosen the correct patch, (b) they had chosen an incorrect patch, or (c) no feedback was available for this trial. Once they had read the feedback screen, clicking the mouse button removed the screen and presented the next image. Once the participants understood the instructions, the researcher started the experiment. These instructions were formulated so as not to include any reference to spatial information; that is, words such *landmarks*, *geometry*, *distance*, *direction*, and *walls* were not used. Furthermore, for comparative purposes (see Kelly & Spetch, 2004a), participants were not guided in their search but rather needed to deduce which patch was correct.

Each program began with a minimum of eight training trials that presented each of the eight training images in random order. The response patch designated as correct was counterbalanced across participants. All training conditions were presented with feedback. If the participant did not choose correctly on 80.0% of the trials, training continued, and accuracy was again calculated after each set of additional eight trials (only the most recent eight trials were used to calculate accuracy). Participants failing to meet the accuracy criterion within the scheduled 45 min were removed from the study, and their data were not used.

Once the participants met the accuracy criterion, they moved on to the testing phase. After participants completed the first testing phase, they were retrained with the opposite condition (i.e., if they were in Group F-G they were retrained and tested with the geometric conditions, and if they were in Group G-F they were retrained and tested with the feature conditions; we used this methodology to allow for comparison of the current experiment with the Kelly & Spetch, 2004a, study). The experiment ended after the second testing phase.

Table 1
Summary of Experimental Testing Conditions for Experiment 1

Group F-G	Group G-F
Feature training	Geometric training
Feature control Geometric only Affine Color only Shape only Distant–far	Geometric control Small Medium Square Small-rotated
Geometric training	Feature training
Geometric control Small Medium Square Small-rotated	Feature control Geometric only Affine Color only Shape only Distant–far

Training and Testing Procedures

Featural training. Eight views of a 3-D rectangular room were shown in random order. In each image, an object with a distinctive color and shape was located at each corner of the room (see Figure 1a): a red triangle, a blue cross, a green cylinder, and a yellow flower-shaped block, in clockwise order. In front of each object was a black response patch. The correct response patch (and hence the correct feature) was maintained throughout training for each participant (as in a reference memory task) but was counterbalanced across participants.

Featural testing. Testing consisted of five blocks, one block for each of the five testing conditions. Each block consisted of three types of trials: baseline trials, control trials, and test trials. In the baseline trials, only the feature control image was presented, and participants received feedback as to whether their choice was correct or incorrect. In the control trials, again only the feature control image was presented, but participants were not given feedback as to whether their choice was correct or incorrect. Test trials manipulated some aspect of the featural cues provided in the images, and no feedback was available. The testing conditions presented were the geometric-only, affine, color-only, shape-only, and distant–far tests (see Figures 1b–1f). The geometric-only test images presented the same rectangular room, but all of the featural cues were removed (see Figure 1b). This test examined whether the participants had encoded the geometric properties of the environment when learning about the features. The affine test images presented the same distinct featural cues as in the feature control images, but each feature was moved one corner counterclockwise (see Figure 1c). This test pitted geometric and featural information against each other by placing the correct feature in an incorrect corner and placing featurally incorrect information in geometrically correct corners. It is important to note that the order of the featural cues was maintained but that the distance between any two features changed. The affine condition tested whether participants responded on the basis of featural or geometric cues when the two cue types gave conflicting information about the location of the correct response patch. In the color-only test, images of the four features had the same distinctive colors as in the feature control images, but the shapes of the features were all changed to a cube (see Figure 1d). This test examined whether the participants had encoded the unique colors of the featural information. The shape-only images again showed the four features as in the feature control images, but all of the features were changed to the same purple color (see Figure 1e). This test examined whether the participants had encoded the unique shape of the featural information. The distant–far test removed all of the featural cues except the cue in the corner along the long wall from the correct corner (see Figure 1f). This test examined whether the participants had encoded this most distant featural cue located in a geometrically incorrect corner.

Geometric training. All general training procedures were identical to feature training, so only the exceptions are explained. Each participant was shown the eight geometric control images showing the room without any distinctive features (see Figure 2a). Without the distinctive features, the

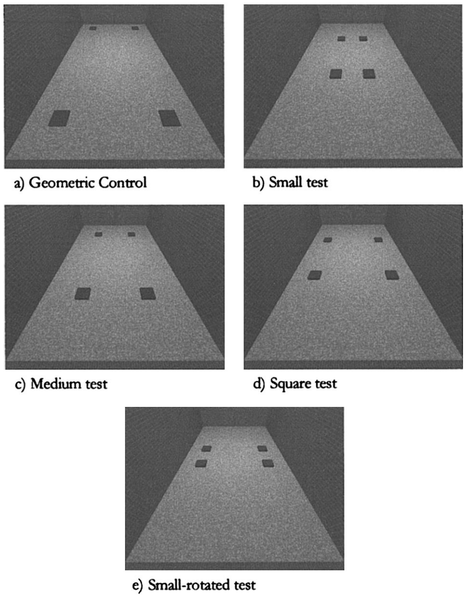

Figure 2. Examples of the images used in geometric testing: (a) geometric control, (b) small, (c) medium, (d) square, and (e) small rotated. All of these examples are illustrated from the same viewpoint to show the test manipulations.

only source of information available to determine the correct corner was the geometric information provided by either the shape of the room and/or the configuration of the four black response patches. Because of the symmetry of the rectangular room, it was 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 (i.e., the geometrically equivalent corner) as correct.

Geometric testing. Geometric testing consisted of four blocks, one for each of the four testing conditions. The testing procedures were the same as those used in feature testing, except that in baseline and control trials the geometric control images (see Figure 2a) were presented, and in test trials, the small, medium, square, and small-rotated images were presented. The small test images presented the same rectangular room, but the rectangle formed by the configuration of the black response patches was reduced by one half of the training size and aligned with the room (see Figure 2b). The medium test images again presented the same rectangular room, but now the configuration of black response patches was reduced by one quarter of the training size and aligned with the room (see Figure 2c). Both the medium and the small test examined whether the configural geometry was encoded in terms of absolute metrics or relative metrics. The square test images presented the same rectangular environment, but the shape of the configuration of black response patches was square instead of rectangular (see Figure 2d). Finally, the small-rotated test images were the same as the small test images, except the configuration of black response patches was presented as orthogonal to the room rather than being aligned with it (see Figure 2e).

Data Analysis

All data presented are from the nonreinforced (i.e., no feedback) control and test trials. To determine how the participants were responding, we calculated the percentage of choices made to each corner averaged over all the participants in a particular group. For the geometric stimuli, we summed responses to the two geometrically correct corners, as discussed above. We carried out data analysis by analyses of variance (ANOVAs) for mixed-factor designs, and, following significant *F* ratios, we used Tukey–Kramer and *t* tests for testing specific comparisons. Furthermore, we examined each statistical test for outliers using the Mahalanobis distance test. Data from outliers were removed only for the affected statistical test. For all statistical tests, our criterion for significance was $p < .05$ unless stated otherwise.

Results

In Group F-G, 1 participant failed to learn the featural training (a man; 48 trials) and 4 participants failed to learn the geometric training (2 men and 2 women; $M = 42.7$ trials). In Group G-F, 1 participant failed to learn the featural training (a woman; 56 trials) and 3 participants failed to learn the geometric training (1 woman and 2 men; $M = 32.0$ trials). If a participant failed to learn the task (i.e., failed to ever achieve at least 80.0% in a block of eight trials or failed to achieve at least 60.0% averaged over all the training trials), his or her data were not used for that particular condition. Although more participants were able to learn the task when featural cues were provided (30 of the 32 participants) than when geometric cues were provided (25 of the 32 participants), this difference was not significant (Fisher's exact test, $p > .1$).

Featural Testing

The following analyses are from a total of 15 participants from Group F-G and 15 participants from Group G-F (unless stated otherwise). To understand whether Group F-G encoded the geometric properties of the environment, even though this was not necessary to solve the task, we first examined responses to the geometric-only test. One outlier (a man) was removed according to the Mahalanobis distance test because his responses were significantly different from those of all other participants ($T^2 = 5.14$, $p < .05$). To determine whether Group F-G encoded geometry, we compared the percentage of total choices made to the two geometrically correct corners with chance-level responding (50.0%) for both men and women. One-sample *t* tests showed that whereas men had encoded the geometric information during featural training, women had not (85.5%), $t(5) = 5.87$, $p < .01$, and (51.5%), $t(7) = 0.42$, $p > .1$, respectively (see Figure 3). Furthermore, a paired *t* test showed no differences between choices to the correct response patch and to the response patch in the geometrically equivalent corner for the male participants (37.7% and 47.7%, respectively), $t(5) = -0.79$, $p > .1$. Together, these results show that the men spontaneously encoded the geometric properties of the environment, whereas women did not.

To examine the effect of featural information, we compared choices to the featurally correct response patch across all test types. A mixed-factor ANOVA with group (F-G and G-F) and sex (men and women) as between-subjects factors and test type (feature control, affine, color only, shape only, and distant–far) as the within-subject factor on accuracy scores showed no effect of group, $F(1, 26) = 1.00$, $p > .1$, and no effect of sex, $F(1, 26) = 0.38$, $p > .1$, but the Group × Sex interaction was significant, $F(1, 26) = 4.31$, $p < .05$. The effect of test type was significant, $F(4, 104) = 17.82$, $p < .0001$. Tukey–Kramer multiple-comparison tests showed that accuracy for the distant–far test (61.3%) was

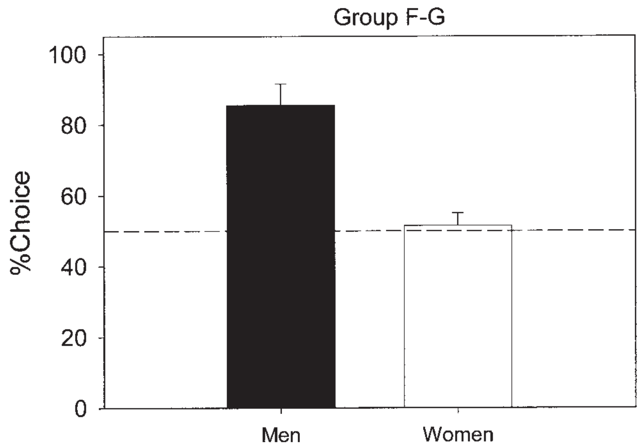

Figure 3. Average percentage of choice to the correct response patch for men and women for the geometric-only test. The dashed line indicates chance level (50%). Error bars represent standard errors of the means. Group F-G = the feature–geometry group.

significantly different from that for all other types, which were not significantly different from each other (feature control, 93.6%; color only, 89.3%; shape only, 87.6%; and affine, 87.4%; all *ps* $<$ .05; see Figure 4). Finally, the Sex × Test Type interaction was also significant, $F(4, 104) = 4.21$, $p < .01$.

Were the participants choosing the correct corner more often than chance in the distant–far test? A one-sample *t* test showed that although men were more accurate, both men and women were choosing the correct corner above chance level (25.0%), $t(14) = 7.90$, $p < .00001$, and $t(14) = 3.86$, $p < .01$, respectively. However, given that Group G-F was trained to encode the geometric properties of the environment and that the men in Group F-G showed spontaneous encoding of geometry, the participants could have distributed their choices equally between the two geometrically correct corners. If this were the case, average accuracy to the correct corner could be significantly greater than 25.0%. If so, we would expect chance to be 50.0%; thus, to examine whether the participants were responding on the basis of geometric encoding, we compared the average accuracy with the 50.0% chance level. In this case, the men but not the women were significantly better than chance, $t(14) = 3.75$, $p < .01$, and $t(14) = 0.01$, $p > .1$, respectively; see Figure 5. Furthermore, the men chose the correct response patch more often than the response patch diagonally opposite to the correct one (72.6% and 17.5%, respectively), $t(14) = 5.14$, $p < .001$. Given that the women did not show control by the distant feature, we reexamined whether the women were dividing their choices randomly, but we were interested to find that they were not. They made significantly more choices to the two geometrically correct corners than to the two geometrically incorrect corners. However, the women chose the two response patches in the geometrically correct corners equally often (49.2% and 29.9%, respectively), $t(14) = 2.06$, $p > .05$. Although the women could not use the single distant feature to find the correct response patch, this limited amount of featural information allowed them to adopt a geometric strategy (see *Discussion*).

Geometric Testing

Data used in the following analyses are from a total of 12 participants in Group F-G and 13 participants in Group G-F. In a rectangular environment void of distinctive featural cues, the participants were unable to differentiate the correct corner from the diagonally opposite corner; hence, we considered these two corners to be geometrically correct, and we summed the responses made to these two corners. To examine the geometric tests, we used the geometric shape of the rectangular environment (i.e., the surface geometry) and not the geometric shape of the four black response patches (i.e., configural geometry). A mixed-factor ANOVA with group (F-G and G-F) and sex (men and women) as between-subjects factors and test type (geometric control, medium, small, small rotated, and square) as a within-subject factor showed no significant effects for group, $F(1, 21) = 1.59$, $p > .1$; sex, $F(1, 21) = 1.20$, $p > .01$; or test type, $F(4, 84) = 2.30$, $p > .05$. Thus,

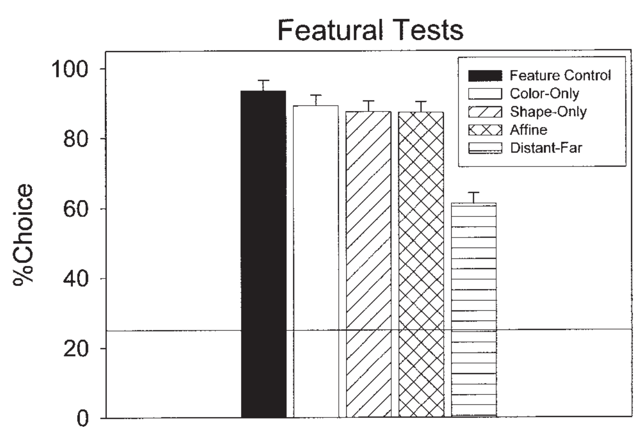

Figure 4. Average percentage of choice to the correct response patch by both groups for the feature control, color-only, shape-only, affine, and distant–far tests. The solid line indicates chance level (25%). Error bars represent standard errors of the means.

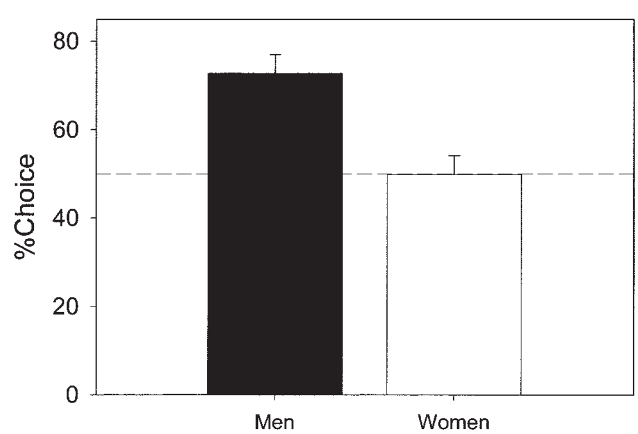

Figure 5. Average percentage of choice to the correct response patch by men and women for the distant–far test. The dashed line indicates chance level (50%). Error bars represent standard errors of the means.

none of the testing conditions differed from the geometric control condition (86.0%; medium, 85.1%; small, 78.7%; small rotated, 75.8%; and square, 77.7%; see Figure 6). It is interesting to note that, when presented with the small-rotated condition, the participants were responding more to the two geometrically correct response patches defined by the surface geometry rather than to the corners defined by configural geometry (76.1% and 23.9%, respectively), $t(24) = 11.09$, $p < .00001$ (see Figure 7). This result shows that when the surface geometry and the configural geometry were placed in conflict, the participants relied more on the surface geometry.

Discussion

In Experiment 1, we found that adults were able to use featural cues to locate the correct corner in 3-D images of a room. Men but not women were able to use the geometric properties of the room to guide their responses when all of the distinctive featural cues were removed (in the geometry-only test). Yet, when provided with even a small amount of distant featural information (in the distant–far test), women could also use a geometric strategy. This result is very interesting because it suggests that women must have encoded the geometric properties of the environment but were unable to access or retrieve this information without the presence of featural information. Sex-based differences in the spontaneous encoding of geometric information have not been explored previously, neither with 2-D images of a rectangular room nor with a navigable version of the rectangular enclosure task. Although previous experiments using a 2-D schematic of a rectangular environment showed that adult humans did show spontaneous encoding of geometry, sex differences were not examined in that study (Kelly & Spetch, 2004a). However, many other investigators have reported sex differences in the use of spatial information in navigational tasks and in tasks that permitted participants the use of distant featural cues (e.g., Astur et al., 1998; Gron, Wunderlich, Spitzer, Tomczak, & Riepe, 2000; Sandstrom et al., 1998; Waller, 2000; for interesting theoretical reviews, see Jones, Braithwaite, & Healy, 2003; and Maguire, Burgess, & O'Keefe, 1999).

Male and female participants were able to accurately use geometric information to concentrate their choices to the two geometrically correct response patches when specifically trained to do so.

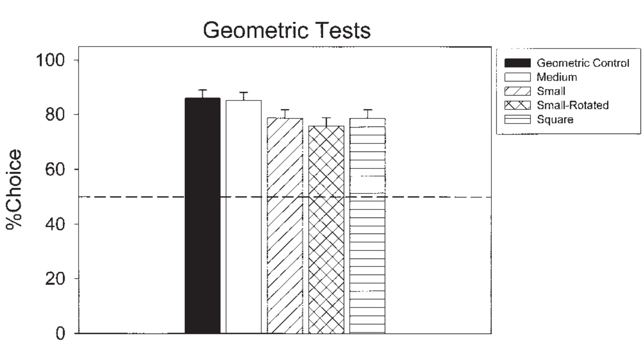

Figure 6. Average percentage of choice to the correct response patches according to surface geometry by both groups for the geometric control, medium, small, small-rotated, and square tests. The dashed line indicates chance level (50%). Error bars represent standard errors of the means.

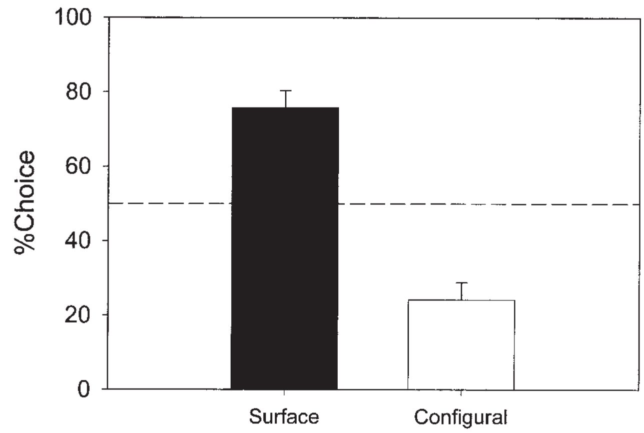

Figure 7. Average percentage of choice to the correct response patches for both groups for the small-rotated test. The dashed line indicates chance level (50%). Error bars represent standard errors of the means.

Furthermore, a comparable proportion of participants learned to use the geometric and featural cues. Previous research using navigable rooms or 3-D models have also shown comparable learning of geometric and featural cues (Gouteux, Vauclair, & Thinus-Blanc, 2001; Hermer & Spelke, 1994). However, this was not so in previous studies using a 2-D schematic of a room (Kelly & Spetch, 2004a, Experiments 1 and 2). Although there are several differences between the current study and the study by Kelly and Spetch, the most salient difference is the availability of 3-D cues, such as depth, and the difference in viewpoint. Providing the participants with depth cues or presenting the images of the room from a side view rather than a top view may make the surface geometry more salient, thus allowing the participants to use this source of information more readily and perhaps more similarly to how they would use these cues in a navigable environment.

The participants showed strong control by the distinctive featural cues in the corners of the room. The encoding of featural cues included both color and shape information. When we systematically removed either the distinctive color or the shape cues, the participants were able to readily use the remaining property to locate the correct response patch. When we removed all but the furthest nongeometrically correct feature, the men were able to use this single feature to locate the correct response patch (although accuracy levels were lower than when all the features were available), whereas the women were not. This suggests that whereas the men might have been encoding the features as landmarks, women might have relied more on a beaconing strategy. The finding that humans encode both color and shape information is very similar to what has been found when adults were presented with a schematic environment (Kelly & Spetch, 2004a), which suggests that 3-D cues may not be necessary to learn simple featural cues in these rectangular types of environments. However, the difference in how the sexes were able to rely on a reduced number of features far from the goal area was not examined in previous studies.

Whereas previous research has shown that adults can use the geometric properties of a rectangular environment and that they can conjoin geometric and featural information, few studies have manipulated the metric properties to examine how geometry is encoded (but see Kelly & Spetch, 2004a, for manipulations involving translation and rotation and Hartley et al., 2004, for manipulations of geometry when distant featural cues are available). We addressed this issue by examining how manipulations of the configuration of black response patches influenced the use of geometry. We found that reducing the size of the configuration of response patches while maintaining the configuration shape did not significantly reduce the participants' ability to continue to respond to the geometrically correct corners (in the medium and small tests). Although, at first glance, it appears that the participants must have encoded the configural geometry in terms of relative metrics, this might not have been the case. In these tests, the participants could have been using either the surface geometry or the configural geometry. When we removed the configural geometry (by configuring the response patches to form a square), leaving only the surface geometry, the participants maintained accurate responding to the geometrically correct corners, which suggests that they must have been using the surface geometry to guide their choices. Further support for this idea could be seen when we pitted surface and configural geometry against each other, in that the participants showed strong reliance on the surface geometry over the configural geometry (in the small-rotation test).

Experiment 2

The results of Experiment 1 provide interesting new insights into how adult humans use featural and geometric information when reorienting in images depicting a 3-D room. Particularly interesting is the strong reliance on the surface geometry over the configural geometry. Previous studies have shown that humans can use configural geometry in open-field settings (Spetch et al., 1997) as well as touch-screen tasks with images of an outdoor scene (Spetch, Cheng, & MacDonald, 1996) and schematic representations of a room (Kelly & Spetch, 2004a). It is likely that the participants in Experiment 1 might also have used configural geometry, had the surface geometry not always been available and reliable. In Experiment 2 we hypothesized that participants would show encoding of configural geometry when it was presented either in the presence or in the absence of surface geometry. Furthermore, we examined whether initial training experience with surface and configural geometry influenced how these types of geometric information were encoded. In particular, we hypothesized that participants would show a preference for the type of geometric information as presented during training.

Method

Participants

The participants were 96 students from the University of Nebraska—Lincoln, 48 women and 48 men, with ages ranging from 18 to 31 years and 18 to 33 years, respectively (with average ages of 19.8 and 20.3, respectively).

Apparatus

The apparatus was identical to the one used in Experiment 1.

Stimuli

The stimuli were the same as in the geometric test of Experiment 1, with two exceptions. First, in a subset of stimuli, the rectangular environment was replaced by a circular environment. Second, the brick texture of the walls in Experiment 1 was replaced by a cork texture (the Tom_Wood texture; see POV-Ray, 2002). The floor, response patches, and viewpoints remained the same.

Two sets of images were created: images of rectangular environments and images of circular environments. The diameter of the circular environment was chosen such that the walls coincided with the corners of the rectangular environment. To examine the influence of surface and configural information, we used five test conditions: (a) The configural geometry was presented as in training (geometric control), (b) the configural geometry was reduced by one quarter from the training size (medium test), (c) the configural geometry was reduced by one half from the training size (small test), (d) the shape of the configural geometry was modified such that the configuration of response patches formed a square rather than a rectangle (square test), and, finally, (e) the configural geometry was as in the small test but rotated by 90° (small-rotated test). To examine the influence of surface geometry, we presented these testing conditions in either a rectangular environment or a circular environment. Refer to Figure 2 (Panels a–e) and Figure 8 (Panels a–e) for examples of the rectangular and circular environments, respectively.

Design

Participants were randomly divided into one of three groups on the basis of type of training: the surface–configural group, the configural-only group, and the surface-only group (see *Training Procedures* for specific details). All participants were tested with the same set of five testing conditions (geometric control, medium, small, small-rotated, and square tests), both in the rectangular and in the circular environment. Thus, the

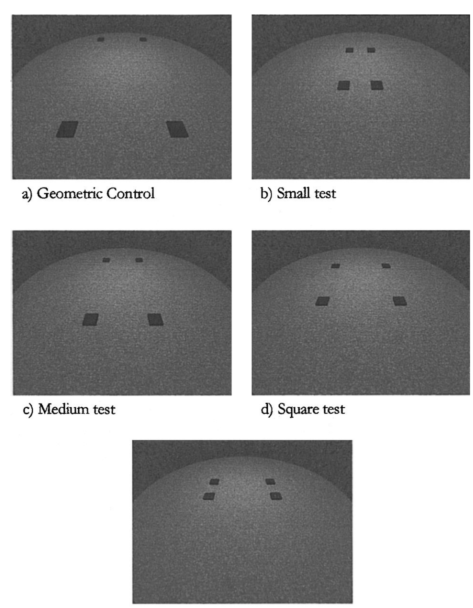

Figure 8. Examples of the images of the circular environment: (a) geometric control, (b) small, (c) medium, (d) square, and (e) small rotated. All of these examples are illustrated from the same viewpoint to show the test manipulations.

experiment had a mixed-factor design with group (surface–configural, configural only, and surface only) and sex (men and women) as between-subjects factors and with environment (rectangular and circular) and configuration (geometric control, medium, small, small-rotated, and square) as within-subject factors.

General Procedures

The general procedures were the same as for geometric training in Experiment 1, with the exception that each participant went through only one training and test stage.

Training Procedures

Participants received training with a set of eight training images. The viewpoint of the camera was identical for all groups. The images were presented in random order, and feedback was provided in each trial. If participants chose the geometrically correct corners on 80.0% of the eight training trials, they were moved on to testing. If participants failed to reach the training criterion, they received an additional block of the same eight training images, and accuracy was again calculated with only the most recent block of eight trials. Training continued until either the accuracy criterion was met or 45 min elapsed. Participants failing to meet the accuracy criterion within the scheduled 45 min were removed from the study, and their data were not used.

Participants were randomly divided into one of three groups on the basis of type of training: The surface–configural group was trained with the four black response patches in a rectangular configuration and in alignment with the rectangular environment. The configural-only group received training with the four black response patches in a rectangular configuration in the circular environment. Finally, the surface-only group received training with the four black response patches in a square configuration in the rectangular environment.

Testing Procedures

All participants were tested with the same set of five testing conditions (geometric control, medium, small, small-rotated, and square tests), in both the rectangular and the circular environments.

Testing was conducted in two blocks. Each block consisted of three types of trials: baseline trials, control trials, and test trials. In the baseline trials, the training images were presented, and participants received feedback as to whether their choice was correct or incorrect. In the control trials, the training images were presented, but participants were not given feedback as to whether their choice was correct or incorrect. In the test trials of the first testing block, the geometry control and square test configurations were presented in both the rectangular and the circular environments. In the second block of testing, the medium, small, and small-rotated test configurations were presented in both the rectangular and the circular environments. In each testing block, 8 baseline, 8 control, and either 32 or 48 test trials (Blocks 1 and 2, respectively) were presented in random order.

Results

A total of 34 participants failed to learn the training conditions (8 participants in the surface–configural group: 4 women and 4 men, $M = 164.0$ trials; 10 participants in the surface-only group: 4 women and 6 men, $M = 37.6$ trials; and 16 participants in the configural-only group: 10 women and 6 men, $M = 70.4$ trials). A similar number of participants learned the task in the surface–configural and surface-only groups as well as in the surface-only and configural-only groups (Fisher's exact test, both $ps > .1$). However, more participants were able to learn the task in the surface–configural group than in the configural-only group (Fisher's exact test, $p < .05$). As in Experiment 1, if a participant failed to achieve 80.0% or better in a block of eight trials or failed to achieve a 60.0% or better average over all the training trials, his or her data were not used in that particular condition. Therefore, the following analyses are based on a total of 62 participants.

A mixed-factor ANOVA with group (surface–configural, configural only, and surface only) and sex (men and women) as between-subjects factors and with environment (rectangular and circular) and configuration (geometric control, medium, small, small-rotated, and square) as within-subject factors showed no effect of group, $F(2, 56) = 0.66$, $p > .10$, and no effect of sex, $F(1, 56) = 0.07$, $p > .10$. The effect of environment was significant, $F(1, 56) = 7.66$, $p < .01$, with accuracy for the circular environment (61.8%) being lower than accuracy for the rectangular environment (66.3%). The effect of configuration was also significant, $F(4, 224) = 30.45$, $p < .0001$. In addition, the following interactions were significant: Group × Environment, $F(2, 56) = 13.65$, $p < .0001$; Group × Configuration, $F(8, 224) = 4.30$, $p < .0001$; Environment × Configuration, $F(4, 224) = 11.74$, $p < .00001$; and Group × Environment × Configuration, $F(8, 224) = 2.55$, $p < .05$. To investigate the experimental importance of the significant interactions, we examined three main questions, as discussed below.

Does Training Influence Whether Participants Can Use Surface Geometry Alone?

To examine whether the specific type of training experienced by the three groups influenced whether participants could use the geometric information provided by the surface geometry, we examined how the three groups responded to the square test presented in the rectangular environment. This condition provided nonisotropic surface geometry but isotropic configural geometry. One-sample *t* tests showed that all three groups were able to use the information provided by the surface geometry to choose the two geometrically correct corners significantly more often than chance (50.0%), $t(23) = 2.80$, $p < .05$; $t(15) = 2.94$, $p < .05$; $t(21) = 6.29$, $p < .00001$, for the surface–configural, configural-only, and surface-only groups, respectively; see Figure 9.

Does Training Influence Whether Participants Can Use Configural Geometry Alone?

To examine whether the type of training influenced whether the participants could use the geometric information provided by the configuration of the response patches, we examined how the three groups responded to the small test presented in the circular environment. This test condition provided nonisotropic configural geometry but isotropic surface geometry. One-sample *t* tests showed that all three groups were able to use the information provided by the configural geometry to choose the two geometrically correct corners significantly more often than chance (50.0%), $t(23) = 4.97$, $p < .0001$; $t(15) = 5.84$, $p < .0001$; $t(21) = 2.45$, $p < .05$, for the surface–configural, configural-only, and surface-only

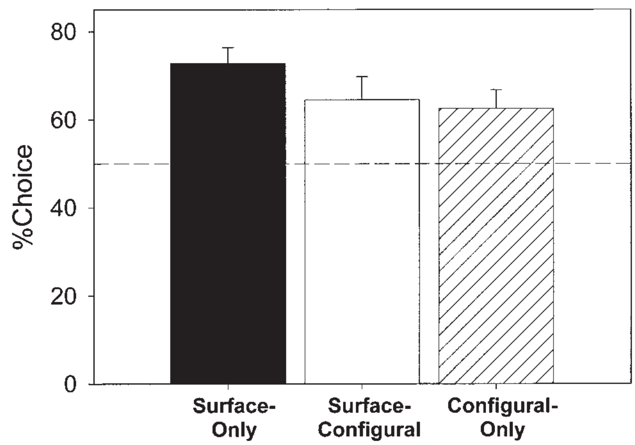

Figure 9. Average percentage of choice to the geometrically correct response patches according to surface geometry for the surface-only, surface–configural, and configural-only groups. The dashed line indicates chance level (50%). Error bars represent standard errors of the means.

groups, respectively; see Figure 10. This result also suggests that the geometric information provided by the configuration of response patches was encoded in terms of relative metrics, because the three groups were able to transfer their knowledge of configural geometry from the much larger configuration learned during training to the smaller configuration of response patches seen in the small test. Furthermore, a repeated-measures ANOVA showed no significant effect of configuration for any of the groups (control, medium, and small), $F(2, 46) = 1.55, p > .1$; $F(2, 30) = 0.36, p > .1$; and $F(2, 42) = 0.49, p > .1$, for the surface–configural, configural-only, and surface-only groups, respectively. These results further support that the configural geometry was encoded with a relative metric.

Does Training Influence How Participants Weigh Information Provided by Surfaces and Configurations When the Two Types of Geometric Cues Are in Conflict?

To examine which source of geometric cues the participants relied on when the surface geometry and configural geometry provided conflicting information regarding the location of the correct response patch, we examined all three groups when presented with the small-rotated test in the rectangular environment. This testing condition provided both nonisotropic surface geometry and nonisotropic configural geometry. However, the location of the correct corner differed depending on which geometry was being used. Paired *t* tests comparing responses made to geometrically correct corners defined by surface geometry or configural geometry showed that the surface-only group responded on the basis of surface geometry (59.0%), $t(21) = 1.93, p < .05$; the configural-only group responded on the basis of configural geometry (71.2%), $t(15) = -3.60, p < .01$; and the surface–configural group divided its choices equally between surface and configural geometry (48.5% and 51.5%, respectively), $t(23) = 0.34, p < .1$; see Figure 11.

Discussion

In Experiment 2, we found that adult humans were able to use both surface and configural geometry in isolation. When participants were presented with only one source of geometric information, either source was sufficient to guide responses, and this use of geometry was independent of whether initial experience was with surface geometry alone, with configural geometry alone, or with both types of geometry present. When the configural geometry underwent size transformations in a room void of distinctive surface geometry (in the circular environment), adults were still able to use the transformed configural geometry to guide their choices. This result shows not only that the participants were encoding the configural geometry but that this information was represented in terms of relative metrics. Perhaps of greatest interest

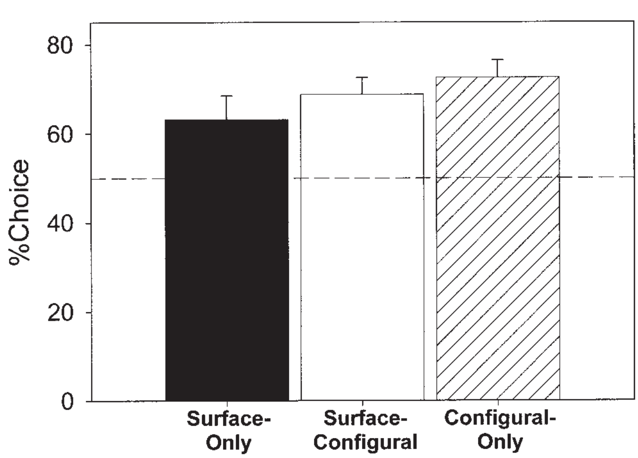

Figure 10. Average percentage of choice to the geometrically correct response patches according to configural geometry for the surface-only, surface–configural, and configural-only groups. The dashed line indicates chance level (50%). Error bars represent standard errors of the means.

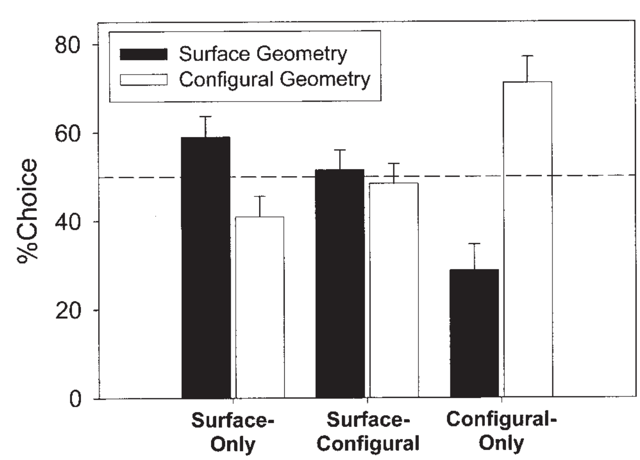

Figure 11. Average percentage of choice to the geometrically correct response patches for the surface-only, surface–configural, and configural-only groups. The dashed line indicates chance level (50%). Error bars represent standard errors of the means.

is our finding that, although surface and configural geometry were used in a similar fashion when presented in isolation, initial training experience became an important factor when these cues provided conflicting information. That is, initial experience with a particular type of geometry influenced how the participants weighed surface and configural geometry. Previous studies have shown that initial experience plays an important role for pigeons in the conjoining of featural and geometric information in a navigable room (Kelly et al., 1998), but, to our knowledge, we are the first to show the influence of initial experience in the encoding of surface and configural geometry by adult humans.

General Discussion

In these experiments, we have examined how adult humans encode geometric and featural information when this information is presented in images of a 3-D environment. Overall, our results are similar to results obtained previously with images of a schematic environment (Kelly & Spetch, 2004a). However, we found many interesting differences, which allow us not only to further our understanding of how humans use featural and geometric cues across different environments but also to examine sex differences in the encoding of these information sources.

Encoding of Featural Information

Men and women readily learned to use featural cues to locate a position in the rectangular environments. When they were learning featural cues, they encoded both the color and the shape properties. This result is similar to that found with adult humans who were presented with images of a schematic environment (Kelly & Spetch, 2004a). However, in contrast to results with a schematic environment, we found that female participants did not encode all of the available features. Kelly and Spetch (2004a) reported that adult humans weighed featural cues differentially, with cues closer to the goal location weighing more heavily than features further away. In our study, women who were presented with images of an environment void of all features except a distant feature were unable to use this single feature to determine the position of the correct response patch. Men, however, did not show such a reduction in performance. Kelly and Spetch were unable to examine sex differences in their study, so we do not know whether the women actually encoded distant features or whether the overall performance of the group misrepresented the women's performance. However, this is unlikely given that the majority of the participants were women (11 women and 5 men).

Encoding of Geometric Information

The results of this study show that adult humans were able to learn to use geometric information to determine a goal location. In contrast to Kelly and Spetch (2004a), learning to locate the correct corner with geometric information only was no more difficult than when featural cues were provided. This difference suggests that having 3-D cues available or presenting the environment from a side view (rather than an overhead view) may be important for enhancing the use of geometric cues of the environment. However, was the representation of the geometric information encoded in a similar way in the two studies? Kelly and Spetch argued that their participants encoded geometry using "orientation- and sense-specific Euclidean properties" (p. 92) and that three independent codes must have been learned, one for each of the different training orientations. This conclusion was supported in two ways. First, fewer participants were able to learn to use the geometric properties when they were presented alone, as opposed to when they were presented in conjunction with distinctive featural cues. Second, after being trained to use the geometric properties alone, participants distributed their choices randomly among the four corners when presented with an environment in a novel orientation not seen during training. Thus, their representation of the geometry must have been orientation and sense specific. In our study, this was most likely not the case. In Experiment 1, the participants in both groups learned their initial task readily. Learning to use geometry was not more difficult than learning to use features. Thus, it is unlikely that the group initially trained with geometry required several codes to learn the task compared with the group initially trained with features present. However, all participants were provided with each training orientation, so we do not know whether we would have found transfer to novel orientations. It would be interesting to find out whether the presence of depth information in our images enhanced the saliency of the geometric information, allowing the participants to encode the geometric information more readily than with the 2-D images presented by Kelly and Spetch.

Gallistel (1990) proposed that geometric information may be provided by surfaces, lines, or points. Yet the majority of studies examining the use of geometric information for reorientation have only used surface geometry (or configural geometry with featural information available). Our experiments further examine Gallistel's definition by investigating whether adults can use the geometric information supplied by the configuration of discrete objects alone. It is interesting that we found that adults could use both the geometric properties of surfaces and the configuration of discrete objects. The weighing of these sources of geometric information depended on the initial experience in an environment. When participants were provided with either source of geometric information alone, they could readily use either surface or configural geometry. However, participants initially trained with nonisotropic surface geometry and isotropic configural geometry relied more heavily on surface geometry in situations of conflict. Conversely, participants initially trained with isotropic surface geometry and nonisotropic configural geometry relied more heavily on configural geometry. Finally, participants trained with both sources of nonisotropic geometry divided their choices equally between the two types of geometry when these cues gave conflicting information about the location of the target.

We also investigated a second important aspect of the encoding of geometric properties—namely, whether geometry is encoded in terms of absolute or relative metrics. The theoretical discussions of the original demonstration of the geometric module by Cheng (1986) assumed that geometry must be encoded with relative metrics: "Only the combination of a sense relation (left-right) and a uniquely metric relation (longer-shorter) renders one pair of diagonally opposite corners in a rectangle geometrically distinct from the other pair" (Gallistel, 1990, p. 199). Gallistel (1990) gives the definition of geometric properties as "a property it possessed by virtue of its position relative to other surfaces, lines and point" (p. 212). However, if the geometric representation were encoded in terms of absolute metrics, this argument would not hold. Kelly and Spetch (2001) tested this assumption and found that pigeons indeed encoded the geometric properties of an enclosed rectangular space using relative metrics. In our study, we examined whether the representation of configural geometry was encoded in terms of relative or absolute metrics. Experiment 1 provided a hint that the participants were using relative metrics. Experiment 2 clearly showed that, in the absence of surface geometry, the participants used relative metrics to guide their choices in tests that manipulated the size of the configural array (in the small, medium, and small-rotated tests in the circular environment). Gallistel's argument referred to relative encoding of the metric properties in rats searching in a navigable rectangular environment. We have been able to extend this to the encoding of configural geometry in adult humans viewing images of a virtual environment.

Relation Between the Encoding of Featural and Geometric Cues

We examined the relation between the encoding of geometric and featural cues in two ways. First, we examined whether the presence of distinctive featural information would overshadow the learning of geometric information. It is interesting that we found that both men and women could learn to use the geometric information when it was presented alone. However, men, but not women showed spontaneous encoding of geometry when trained initially with featural cues. Kelly and Spetch (2004a) reported that human adults showed spontaneous encoding of geometry with schematic images, but they were unable to analyze their data by sex, so we do not know whether the women actually showed spontaneous geometric encoding. For instance, it is possible that the relatively poor performance seen in their geometry test (62.6% accuracy for Group F-G) might have been due to the lack of geometric encoding by the women. Many studies have reported that adult humans do indeed spontaneously encode the geometric properties of a rectangular environment when trained with features present. Hence, it would be very important to understand whether a sex difference is actually present. Furthermore, it would be important to determine whether women are indeed able to use geometric information in images of schematic environments but not in images of a 3-D environment.

Second, we examined how adult participants weigh featural and geometric information when the two sources provided conflicting information about the goal location. We found a strong reliance on featural cues. In Experiment 1, the participants did not respond differently in situations in which geometric and featural cues were in conflict. This result matches those reported using schematic images of a rectangular environment (Kelly & Spetch, 2004a). It would be interesting to examine whether participants would show such strong encoding of featural cues if these cues were part of the environmental surface (i.e., walls painted a different color) rather than discrete objects.

Sex Differences

Studies examining how men and women use spatial cues for navigation have reported some interesting differences in how this information is remembered and subsequently used. Women tend to use a topographical approach to learn environments in tasks ranging from simple paper-and-pencil maps to real-world navigation (e.g., Astur et al., 1998; Dabbs, Chang, Strong, & Milun, 1998; MacFadden, Elias, & Saucier, 2003; Sandstrom et al., 1998; and Saucier et al., 2003). Men show a tendency to use cardinal directions and distance information in similar tasks. In our current experiment, we found that men but not women showed spontaneous encoding of geometric information when trained with featural information present. This is entirely consistent with results reported in navigation-based studies. To navigate successfully, an individual first needs to determine heading or needs to orient. It is thus particularly interesting that we found sex differences in a reorientation task. The differential use of featural and geometric cues by women and men for reorientation in a navigable environment has, to our knowledge, not yet been investigated.

In summary, our results show that adults encode featural and geometric cues in a nonimmersive reorientation task. In general, these results are similar to those reported in navigable environments and in 2-D schematic environments. However, closer examination of how the participants were using these cues revealed many interesting differences in terms of both sex differences and, possibly, task-related differences. Examining how adults use featural and geometric cues across very different environments has many important implications for furthering our understanding not only of general navigational abilities but also of sex differences in the way this information is effectively used and communicated to others.

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