Beacons and surface features differentially influence human reliance on global and local geometric cues when reorienting in a virtual environment

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A B S T R A C T

In the reorientation literature, non-geometric cues include discrete objects (e.g., beacons) and surface-based features (e.g., colors, textures, and odors). To date, these types of non-geometric cues have been considered functionally similar, and it remains unknown whether beacons and surface features differentially influence the extent to which organisms reorient global and local geometric cues. In the present experiment, we trained human participants to approach a location in a trapezoid-shaped enclosure uniquely specified by global and local geometric cues. We explored the role of beacons on the use of geometric cues by training participants in the presence or absence of uniquely-colored beacons. We explored the role of surface features on the use of geometric cues by recoloring two adjacent walls at the correct location and/or adding a line on the floor which corresponded to the major principal axis of the enclosure. All groups were then tested in novel-shaped enclosures in the absence of unique beacons and surface features to assess the relative use of global and local geometric cues. Results suggested that beacons facilitated the use of global geometric cues, whereas surface features either facilitated or hindered the use of geometric cues, depending on the feature.

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Multiple cues are available to mobile organisms attempting to determine orientation with respect to their environment. For example, geomagnetic fields, celestial bodies, and vestibular cues have been identified as contributing to orientation ability (for a review, see Healy, 1998). In the reorientation literature, these spatial cues have generally been categorized as either geometric (e.g., angles, distances) or non-geometric cues (e.g., objects, colors; for a review, see Gallistel, 1990). One pervasive method for investigating these types of reorientation cues involves training subjects to locate a corner in a rectangular enclosure marked by distinct beacons. Following training, researchers often manipulate the shape of the environment and/or the location of the beacons to determine the extent to which reorientation relied on geometric and non-geometric cues (for a review, see Cheng and Newcombe, 2005, 2006; Tommasi et al., 2012).

Initially, geometric cues appeared to be considered a single functional class of spatial cues. Global geometric cues, such as the major principal axis of space (which passes through the centroid and approximate length and width of the entire space, respectively), and local geometric cues, such as wall lengths and corner angles, were not considered as independent cues for reorientation (e.g., see Cheng, 1986; Miller and Shettleworth, 2007). This unitary classification of geometric cues appeared to occur because of the difficulty in isolating the use of global versus local geometric cues for reorientation. Recently, Bodily et al. (2011) developed a reorientation task that allowed for the discrimination between the use of global and local geometric cues. Specifically, two groups of human participants were rewarded for searching in an isosceles trapezoid-shaped enclosure at locations that maintained the reliability of local geometric cues (wall lengths and corner angles) across groups but manipulated the reliability of global geometric cues (i.e., the major principal axis) between groups. Specifically, one group was rewarded for searching only at the right-hand side of the major principal axis whereas another was rewarded for searching at both the left- and right-hand sides of the major principal axis. When tested in a rectangle, a parallelogram, and the parallelogram’s mirror equivalent, group differences emerged with respect to the geometric cues utilized for reorientation. The group trained with unreliable global but reliable local geometric cues exclusively reoriented using local geometric cues. In contrast, the group trained with reliable global and local geometric cues reoriented using both global and local geometric cues. Our present understanding, then, is that humans (and other animals) are able to reorient via global geometric cues (e.g., Bodily...
et al., 2011; Sturz et al., 2011) and local geometric cues independently (e.g., Bodily et al., 2011; Lubyk et al., 2012), and that global and local geometric cues are best categorized as separate functional classes.

Similarly, we argue that conceptualizing non-geometric cues as a single functional class is potentially problematic for the investigation of spatial reorientation. Non-geometric cues, often broadly referred to as featural cues (e.g., Cheng and Newcombe, 2005), include both surface-based features (e.g., colors, textures, and odors), which are directly tied to a surface of the enclosure (e.g., a blue wall), and discrete objects (e.g., beacons, landmarks), which are placed inside or outside of the enclosure. Perhaps the tendency to group surface-based features and discrete objects into a single class was due to their functional similarity—both types of cues may be utilized to reorient. However, categorizing all non-geometric cues as a single functional class may fail to make potentially important distinctions between these different types of cues. For example, systematic investigations of the differential influence of intramaze and extramaze cues in the place learning literature revealed functional differences between cue types which helped account for divergent findings in the literature (e.g., Brown and Bing, 1997; Olton and Collison, 1979; see also Babb and Crystal, 2003). Similarly, investigating how surface-based features and discrete objects differentially affect reorientation may reveal important differences which may shed light on divergent findings and advance theoretical accounts of spatial reorientation.

As James (1890) pointed out over a century ago, psychological processes work “under conditions; and the quest of the conditions becomes the psychologist’s most interesting task” (p. 3; for a similar charge, see Cheng, 2008). Although conditions such as environment size (e.g., Learmonth et al., 2002; Ratliff and Newcombe, 2008; Sturz et al., 2012) and environment shape (e.g., Sturz et al., 2011; Sturz and Bodily, 2011) have been shown to influence reliance on global and local geometric cues, questions regarding the effects of beacons and surface-based features on the use of global and local geometric cues remains unclear (e.g., Cheng and Gallistel, 2005; Cole et al., 2011; McGregor et al., 2006; Pearce et al., 2006; Pecchia and Vallortigara, 2012). The motivation of this study was to further illuminate the conditions under which global and local geometric cues are used. In particular, we attempted to uncover potential similarities and differences regarding the influence of surface-based features and beacons on reorientation by global and local geometric cues.

In the present experiment, we utilized the methodology established by Bodily et al. (2011) to explore the extent to which beacons and surface-based features may influence the use of global and local geometric cues for reorientation. The purpose of this study was two-fold. First, we investigated the extent to which the presence of surface-based features or beacons separately influenced the use of global and local geometric cues. Second, we investigated the extent to which combinations of surface-based features and beacons influenced the use of global and local geometric cues.

We trained eight groups of human participants, in a virtual environment, to respond to a location in an isosceles trapezoid-shaped enclosure (see Fig. 1). The use of the trapezoid-shaped enclosure is of critical importance. First, like a kite, an isosceles trapezoid is rotationally asymmetric. That is, opposite corners of an isosceles trapezoid are made up of different local geometric cues. Second, like a rectangle, the axis of symmetry bisects opposite sides (whereas the axis of symmetry of a kite bisects opposite angles). That is, the principal axis of space bisects opposite sides of an isosceles trapezoid, allowing a meaningful comparison between performance in an isosceles-trapezoid-shaped enclosure and performance in a rectangular enclosure with regard to dependence on global geometric cues. Finally, these characteristics allowed us to

<table>
<thead>
<tr>
<th>Table 1: Predicted allocation of responses to geometrically-correct locations relative to chance performance (0.5) by cue type.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Testing enclosure</strong></td>
</tr>
<tr>
<td><strong>Cue type used to orient</strong></td>
</tr>
<tr>
<td>Global cues</td>
</tr>
<tr>
<td>Local cues</td>
</tr>
<tr>
<td>Global &amp; local cues</td>
</tr>
</tbody>
</table>

train participants to approach a corner that was uniquely specified by a combination of global (i.e., right-hand side of the major principal axis of space) and local (i.e., short wall left and right, and obtuse corner angle) geometric cues, such that responding could come to depend on global, local, or both types of geometric cues.

To explore the effect of beacons on the use of geometric cues, we trained participants either in the presence or absence of uniquely-colored beacons at each response location. To explore the effect of surface-based features on the use of geometric cues, we trained participants in one of four different Surface-Feature conditions: None, Walls, Floor, or Both. In the None condition, we did not add unique surface-based features to any surface of the enclosure. In the Walls condition, we recolored the two adjacent walls at the correct corner to be a darker shade of gray than the opposite walls. In the Floor condition, we added a black line on the floor which corresponded with the major principal axis of the enclosure (see Krider et al., 2001). In the Both condition, we recolored the adjacent walls at the correct corner and added the black line on the floor.

Following training, we tested participants in the absence of unique beacons and surface-based features in the trapezoid and three additional enclosures. The trapezoid test enclosure allowed us to assess whether participants depended primarily on global or local geometric cues when the non-geometric cues were removed. The other test enclosures allowed us to assess dependence on global geometry in isolation (i.e., the rectangle enclosure), in alignment with the trained local geometric cues (i.e., the parallelogram 1 enclosure) or in conflict with the trained local geometric cues (i.e., the parallelogram 2 enclosure). As shown in Table 1, the predicted allocation of responses to the top-right and bottom-left corners (henceforth referred to as geometrically-correct locations) in each test enclosure depends on which cues are used to reorient. For example, as the rectangle enclosure does not contain the trained local geometric cues (e.g., 120° corner angle), responding at the geometrically-correct locations is predicted only if global cues are used. Alternatively, as the parallelogram 2 enclosure contains trained local geometric cues at incongruent corners relative to the training trapezoid, responding at the geometrically correct corners is predicted if only global geometric cues are used, while responding to the opposite corners (top-left and bottom-right) is predicted if only local geometric cues are used. Overall, this design allows us to assess the extent to which conditions involving beacons and surface-based features influenced the relative use of global and local geometric cues to reorient.

1. Method

1.1. Participants

One hundred twelve undergraduate students (48 males and 64 females) served as participants. Participants received extra class-credit or participated as part of a course requirement.

1.2. Apparatus

An interactive, dynamic three-dimensional virtual environment was constructed and rendered using Valve Hammer Editor and
Surface-Feature Training Enclosures

![Surface-Feature Training Enclosures](image)

Testing Enclosures

- **Trapezoid**
- **Rectangle**
- **Parallelogram 1**
- **Parallelogram 2**

TL = Top Left
TR = Top Right
BL = Bottom Left
BR = Bottom Right

- ○ = Trained Location
- ○ = Response Location
- TL = Start Location

<table>
<thead>
<tr>
<th>TL</th>
<th>BL</th>
<th>TR</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

= Major Principal Axis (illustration only)
= Added Line
= Shaded Wall

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**Fig. 1.** Sample images from the first-person perspective (top) of the virtual-environment training enclosures appear above the schematics of training trials for each group. Below these are shown the schematics of the testing enclosures experienced by all participants. For illustrative purposes, the gray quad-arrows mark the position where participants entered the virtual enclosures for all training and testing trials. Large unfilled dotted circles indicate training location for all groups. Small, filled circles represent response locations where colored spherical beacons were visible for participants in the Beacons-Present conditions but not for participants in the Beacons-Absent conditions. Dotted lines represent the major principal axis of space for each testing enclosure (calculated using FreeMat v4.1 software).

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run on the Half-Life Team Fortress Classic platform. A personal computer, 21-in. flat-screen liquid crystal display (LCD) monitor, gamepad joystick, and speakers served as the interface with the virtual environment. The monitor (1680 × 1050 pixels) provided a first-person perspective of the virtual environment (see top panels, Fig. 1). Participants used the joystick on the gamepad to navigate within the environment. Speakers emitted auditory feedback. Experimental events were controlled and recorded using Half-Life Dedicated Server on an identical personal computer.

1.3. Stimuli

Dimensions are long wall(s) × short walls × height and measured in virtual units (vu; 1 vu = ~2.54 cm). Texture brightness is reported in luma, a standard measure of the brightness of a digital image which may range from 0 (black) to 255 (white). Four virtual enclosures were created (see Fig. 1): Trapezoid (550 × 275 × 260 vu), Rectangle (550 × 275 × 260 vu), Parallelogram 1 (550 × 275 × 260 vu), and Parallelogram 2 (550 × 275 × 260 vu). Corner angles for the trapezoid-shaped enclosures were 60° for both acute angles and 120° for both obtuse angles. Corner angles in the parallelograms were also 60° for both acute angles and 120° for both obtuse angles. Corner angles for the rectangle were 90°. Please note that all short walls shown in Fig. 1 were identical in length. All wall surfaces were textured with light-gray "concrete" [brightness (in luma): M = 187.7, SD = 7.19; Adobe Photoshop 12.1], the floor surface was textured with gray tile, and the ceiling was black. Depending on the condition, during training the adjacent walls at the goal location were textured with a dark-gray "concrete" [brightness (in luma): M = 113.9, SD = 7.08].
and/or a solid black line (width = 8 vu) was applied to the floor. For half of the participants, enclosures contained four spherical, semi-transparent beacons (48 x 48 x 48 vu). During training, a red, blue, yellow or green beacon appeared consistently in the same corner of the enclosure, hovering above the floor (40 vu from center of beacon to floor). During testing, all beacons were semi-transparent white. Please note that the small size of the beacons, relative to the walls of the enclosure, and their semi-transparency prevented the beacons from obstructing the corners of the enclosure.

1.4. Procedure

Participants were informed to navigate to the location that transported them to the next virtual room and to move via the joystick on the gamepad: ↑ (forward), ↓ (backward), ← (rotated view left), and → (rotated view right). Participants selected a location by walking into it. Selection of the rewarded location resulted in auditory feedback (bell sound) and a 7-s inter-trial interval (ITI) in which the monitor went black and participants progressed to the next trial. Selection of a non-rewarded location resulted in different auditory feedback (buzz sound) and required participants to continue searching.

1.4.1. Training

Training consisted of 12 trials. Participants were randomly assigned to a combination of Beacon-Status (Present or Absent) and Surface-Feature (None, Walls, Floor, or Both) conditions, thereby creating eight groups (see Fig. 1). Gender and number of participants were balanced across groups. In the Beacons-Present condition, the response locations (i.e., each corner of the enclosure) were marked with uniquely colored spherical beacons. In the Beacons-Absent condition, response locations were unmarked. In the None Surface-Feature condition, no unique surface features were added to the walls or floor. For the Walls Surface-Feature condition, the two adjacent short walls at the rewarded corner location were textured with a darker gray “concrete” than the other two walls. For the Floor Surface-Feature condition, a solid black line was added on the floor which ran the length of the enclosure and corresponded to the enclosure’s major principal axis. For the Both Surface-Feature condition, both the recolored walls and the solid black line were present.

For all groups, the rewarded location was always located in the top-right corner (see Fig. 1) such that searching at the egocentric right-hand side of the major principal axis and at a location specified by short wall left, short wall right, and obtuse angle was rewarded. Participants began each trial in the center of the Trapezoid enclosure (marked with a quad arrow in Fig. 1) with a heading that was randomly selected from 0° to 270° in increments of 90°.

1.4.2. Testing

Testing consisted of 60 trials composed of 12 five-trial blocks. Each trial block was composed of four Training trials and one Test trial. Training trials presented during Testing were identical to those experienced during Training for each group (see above). The order of the Training and Test trials was randomized within each block. For each Test trial, one of four enclosures was presented: Trapezoid, Rectangle, Parallellogram 1, or Parallellogram 2. Each enclosure was presented once without replacement until all four had been presented. Each enclosure was presented three times (total of 12 test trials). Participants made one response during Test trials which resulted in no auditory feedback followed by the 7-s ITI and progression to the next trial. Participants began each Testing trial in the center of the enclosures (marked with quad arrows in Fig. 1) with a heading that was randomly selected from 0° to 270° in increments of 90°.

For all participants, the surface features and unique beacons were absent during test trials. That is, all of the walls were the same color and the floor was free of the black line for all participants. For participants in the Beacons-Present condition, the uniquely colored beacons were all replaced with white beacons. For participants in the Beacons-Absent condition, the response locations remained unmarked, as they were in training (see Fig. 1).

2. Results

2.1. Training

 Acquisition performance was measured by coding the first location that a participant visited (i.e., the first response) in each trial as being either correct (i.e., the rewarded location) or incorrect (i.e., one of the other 3 locations), and then by calculating the proportion correct per two-trial block. A three-way mixed analysis of variance (ANOVA) on acquisition performance with Block (1–6), Beacon Status (Present, Absent), and Surface Feature (None, Walls, Floor, Both) as factors revealed main effects of Block, F(5, 520) = 46.30, p < .001, Beacon Status, F(1, 104) = 49.26, p < .001, and Surface Feature, F(3, 104) = 2.75, p < .05. The Beacon Status x Surface Feature interaction was also significant, F(3, 104) = 3.92, p = .01. None of the other interactions were significant, F(1, 129) < .26. Overall, acquisition performance increased across blocks, as confirmed by a significant linear component of the trend analysis on the Block factor, F(1, 104) = 131.22, p < .001, suggesting that all groups improved across training blocks.

Fig. 2 plots the Surface Feature x Beacon Status interaction. As shown, the interaction was due to equivalent performance across Surface-Feature conditions in the presence of beacons, and differences in performance across Surface-Feature conditions in the absence of beacons. These results were confirmed by one-way ANOVAs on overall acquisition performance with Surface Feature (None, Walls, Floor, Both) as a factor, conducted separately for each Beacon Status condition. For Beacons-Present, there was no effect of Surface Feature, F(3, 52) = 0.17, p = .92. However, for Beacons-Absent, there was a main effect of Surface Feature, F(3, 52) = 4.68, p < .01. In the absence of beacons, the None condition was significantly different from the Walls condition (Tukey’s post hoc test, p < .01), but no other comparisons were significantly different (ps > .06). Lastly, we compared Beacons-Present and Beacons-Absent groups within each Surface-Feature condition. The Beacons-Present performed significantly better than the Beacons-Absent groups in the None, Floor, and Both Surface-Feature conditions, independent samples t-tests, t(26) > 2.3, ps < .03. However, the Beacons-Present and Beacons-Absent groups did not differ in the Walls Surface-Feature condition, independent-samples t-test, t(26) = 1.42, p = .17. Overall, these results suggest that the presence of beacons facilitated acquisition, and that, in the absence of beacons, the shaded walls facilitated acquisition.

Fig. 3 (left panels) shows the acquisition performance across two-trial training blocks for Beacons-Present and Beacons-Absent conditions, plotted separately for each Surface-Feature condition. All groups learned to approach the correct corner by the third block of training. These results were confirmed by comparing the acquisition performance of each group to chance (0.25) across training blocks 3–6, one-sample t-tests, t(13) > 2.33, ps < .037. Additionally, all groups reached asymptotic performance by the fourth block of training. Acquisition performance in training block 6 did not differ from training blocks 4 or 5 for any group, paired-sample t-tests, t(13) < 1.88, ps > .08.

To summarize, the results from training suggest that the presence of unique beacons at each response corner facilitated acquisition independently from surface features. In the absence
of unique beacons, surface feature which uniquely specified the correct location (i.e., the Walls condition) also facilitated acquisition. Finally, all of the groups reached and maintained a consistent, above-chance, level of accuracy throughout the last three blocks of training. This result is particularly important, as above-chance acquisition performance is necessary in order to interpret performance on test trials.

2.2. Testing

Test trials assessed the extent to which responding depended upon global and/or local geometric cues. To this end, test enclosures were devoid of the added surface features and, for the Beacons-Present groups, all beacons were white. First, we assessed whether groups successfully reoriented in the absence of beacons and/or surface features by analyzing the distribution of responses to all four corners (i.e., response locations) of the trapezoid testing enclosure. Additionally, each corner of the trapezoid testing enclosure had a unique combination of geometric cues in common with the trained corner (i.e., top-left: no common cues, top-right: global and local cues, bottom-left: global cues, bottom-right: local cues). By analyzing the proportion of responses allocated to each corner, we assessed whether participants depended on global and/or local geometric cues to reorient.

Next, to further assess the extent to which responding depended upon global and local geometric cues, we analyzed the mean proportion of responses allocated to the geometrically-correct locations (i.e., top-right and bottom-left corners) across all testing enclosures. Lastly, to assess the combined effects of beacons and surface features on the use of global and local geometric cues, we conducted planned comparisons analyzing the mean proportion of responses allocated to the geometrically-correct corners of each testing enclosure across Beacons-Present and Beacons-Absent groups within each Surface-Feature condition. Table 1 summarizes how the use of each type of geometric cue (i.e., global, local, global and local) is predicted to affect the allocation of responses to the geometrically-correct corners in each testing enclosure.

2.2.1. Trapezoid testing enclosure

Fig. 3 (right panels) shows the mean proportion of responses to each corner (i.e., response location) of the trapezoid testing enclosure for Beacons-Present and Beacons-Absent conditions, plotted separately for each Surface-Feature condition. For each group, the number of responses to each response location (i.e., TL, TR, BL, BR) across the three trapezoid testing trials was analyzed via \( \chi^2 \) goodness-of-fit tests against an expected uniform distribution (.25) to assess the extent to which participants reoriented in the absence of unique beacons and/or surface features. The Beacons-Present and Beacons-Absent groups in the None, Walls, and Floor Surface-Feature conditions were oriented in the trapezoid test enclosure, \( \chi^2(3, N=42) > 13.24, ps < .01 \). Additionally, one-sample t-tests (\( \alpha = .05 \)) were conducted to determine the corners at which the mean proportion of responses differed from chance (see Fig. 3, right panels). Although all of these groups were significantly oriented in the trapezoid test enclosure, differences in the distributions of responses suggest that the presence of beacons and/or surface features during training influenced the extent to which global and local geometric cues were used in testing.

In the Both Surface-Feature condition (Fig. 3, bottom-right panel), the distribution of responses of the Beacons-Present and Beacons-Absent groups did not significantly differ from an expected uniform distribution, \( \chi^2(3, N=42) < 6.57, ps > .08 \). These results may suggest that the presence of both surface features, regardless of the presence or absence of beacons, may have hindered the use of global and local geometric cues. However, both groups equally distributed their responses among the top-right (global and local cues), bottom-left (global cues), and bottom-right (local cues) locations and allocated significantly fewer responses to the top-left location (no congruent cues) than expected by chance, one-sample t-tests, \( t(13) > 2.33, ps < .04 \). These results may suggest that participants were oriented, and that responding depended upon both global and local geometric cues equally. Their results on the other testing enclosures revealed which of these two interpretations is best.

2.2.2. All testing enclosures

A three-way mixed ANOVA on mean proportion of responses to the geometrically-correct locations (i.e., top-right and bottom-left) with Beacon Status (Present, Absent), Surface Feature (None, Walls, Floor, Both), and Enclosure Type (Trapezoid, Rectangle, Parallelogram 1, Parallelogram 2) as factors, revealed main effects of Surface Feature, \( F(3, 104) = 2.86, p < .05 \), and Enclosure Type, \( F(3, 312) = .26.45, p < .001 \). Additionally, the Beacon Status \( \times \) Surface Feature, \( F(3, 104) = 4.07, p < .01 \), Beacon Status \( \times \) Enclosure Type, \( F(3, 312) = 4.57, p < .01 \), and the Surface Feature \( \times \) Enclosure Type, \( F(9, 312) = 2.24, p < .05 \) interactions were significant. Neither the effect...
Fig. 3. Training acquisition and trapezoid-test response distributions for Beacons-Present (filled) and Beacons-Absent (unfilled) groups plotted separately by Surface-Feature conditions. Left panels plot mean proportion of correct first responses across training in two-trial blocks. Right panels plot mean proportion of responses across corners (response locations) of the trapezoid-test enclosure in the absence of surface features and unique beacons. Dotted borders represent measures that do not differ from chance. Dashed lines represent chance performance (0.25). Error bars represent standard errors of the means.

of Beacon Status nor the interaction of Beacon Status × Surface Feature × Enclosure Type was significant, $F$s < 1, $ps > .41$. Separate follow-up analyses were conducted to determine the source of these interactions.

Fig. 4 (top panel) shows the Beacon Status × Surface Feature interaction. As shown, the interaction was due to the Beacons-Absent group allocating more responses to the geometrically-correct locations than the Beacons-Present group in the Floor Surface-Feature condition, independent samples $t$-test, $t(26) = 2.48$, $p = .02$. There was no effect of the Beacon Status in the other three Surface-Feature conditions, $ts(26) < 1.83$, $ps > .078$. These results suggest that the presence of beacons may have
Testing Performance across Surface Features by Beacon Status

Fig. 4. Top Panel. Mean proportion of responses to the geometrically-correct locations (i.e., top-right and bottom-left) during testing for the Beacons-Present (filled) and Beacons-Absent (unfilled) groups plotted across Surface-Feature conditions (i.e., the Beacon Status x Surface Feature interaction). Middle Panel. Mean proportion of responses to the geometrically-correct locations during testing for the Beacons-Present and Beacons-Absent groups plotted across testing enclosures (i.e., Beacon Status x Enclosure Type interaction). Bottom Panel. Mean proportion of responses to the geometrically-correct locations during testing for each Surface-Feature condition plotted across testing enclosures (i.e., Surface Feature x Enclosure Type interaction). Dashed lines represent chance (0.5). Error bars represent standard errors of the means.

weakly facilitated the use of global geometric cues in the None, Walls, and Both, but not in the Floor, Surface-Feature conditions.

Fig. 4 (middle panel) shows the Beacon Status x Enclosure Type interaction. As shown, the interaction was due to the Beacons-Absent groups allocating significantly more responses to the geometrically-correct locations in the Parallelogram 1 enclosure and significantly fewer responses to the geometrically-correct locations in the Parallelogram 2 enclosure than the Beacons-Present groups, independent samples t-tests, ts(110) > 2.05, ps < .05. However, there was no effect of Beacon Status in the Trapezoid or
2.3. Planned comparisons

Fig. 5 shows the mean proportion of responses to the geometrically-correct locations for Beacons-Present and Beacons-Absent groups across Testing Enclosures, plotted separately for each Surface-Feature Condition. To more directly investigate the effects of beacons and surface features on the use of global and local geometric cues, separate two-way mixed ANOVAs on mean proportion of responses to the geometrically-correct locations (i.e., top-right and bottom-left) with Enclosure Type (Trapezoid, Rectangle, Parallelogram 1, Parallelogram 2) and Beacon Status (Beacons Present, Beacons Absent) as factors were conducted for each Surface-Feature condition. Additionally, separate one-sample t-tests were conducted to compare each group’s performance in each testing enclosure to chance (0.5). Table 2 provides a summary of the obtained results.

2.3.1. Surface feature: None

There was a main effect of Enclosure Type, \( F(3, 78) = 17.81, p < .001 \), a significant Enclosure Type \( \times \) Beacon Status interaction, \( F(3, 78) = 5.13, p < .01 \), but no effect of Beacon Status, \( F(1, 26) = 3.36, p = .08 \). The effect of Enclosure Type was due to significantly fewer geometrically-correct responses in the Parallelogram 2 enclosure than the other three enclosures, \( p < .002 \), and significantly fewer geometrically-correct responses in the Rectangle enclosure than the Parallelogram 1 enclosure, \( p < .01 \). The interaction was due to the Beacons-Absent group making significantly more responses in the Parallelogram 1 enclosure, independent-samples t-test, \( t(26) = 2.15, p = .04 \), and significantly less in the Parallelogram 2 enclosure, independent-samples t-test, \( t(26) = 3.08, p < .01 \), to the geometrically-correct locations than the Beacons-Present group. Additionally, the Beacons-Present group made more geometrically-correct responses than expected by chance in the Trapezoid, Parallelogram 1, and Parallelogram 2 enclosures, independent-samples t-tests, \( t(26) < 1.00, p > .30 \), but not the Rectangle enclosure, \( t(26) = 1.76, p = .15 \).
Table 2  
Summary of the obtained allocation of responses to geometrically-correct locations relative to chance performance (0.5) for each group.

<table>
<thead>
<tr>
<th>Training condition</th>
<th>Testing enclosure</th>
<th>Rectangle</th>
<th>Parallelogram 1</th>
<th>Parallelogram 2</th>
<th>Cue type(s) used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Feature: None</td>
<td>Beams Present</td>
<td>Above</td>
<td>Above</td>
<td>Equal</td>
<td>Global &amp; Local</td>
</tr>
<tr>
<td></td>
<td>Beams Absent</td>
<td>Equal</td>
<td>Above</td>
<td>Below</td>
<td>Local</td>
</tr>
<tr>
<td>Surface Feature: Walls</td>
<td>Beams Present</td>
<td>Above</td>
<td>Above</td>
<td>Equal</td>
<td>Global &amp; Local</td>
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<tr>
<td></td>
<td>Beams Absent</td>
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</tr>
<tr>
<td>Surface Feature: Floor</td>
<td>Beams Present</td>
<td>Above</td>
<td>Equal</td>
<td>Global &amp; Local</td>
<td></td>
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<tr>
<td></td>
<td>Beams Absent</td>
<td>Equal</td>
<td>Above</td>
<td>Global &amp; Local</td>
<td></td>
</tr>
<tr>
<td>Surface Feature: Both</td>
<td>Beams Present</td>
<td>Above</td>
<td>Above</td>
<td>Equal</td>
<td>Global &amp; Local</td>
</tr>
<tr>
<td></td>
<td>Beams Absent</td>
<td>Equal</td>
<td>Equal</td>
<td>–</td>
<td></td>
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</tbody>
</table>

* Two of the three predictions held, and the third trended in the predicted direction.

b Obtained results trended below chance.

c Obtained results trended above chance.

Rectangle, and Parallelogram 1 enclosures, independent-samples t-tests, t(13) = 2.77, p < .02, but not in the Parallelogram 2 enclosure, independent-samples t-test, t(13) = .23, p > .82. In contrast, the Beams-Absent group made significantly more geometrically-correct responses than expected by chance in the Trapezoid and Parallelogram 1 enclosures, independent-samples t-tests, t(13) = 3.22, p < .01, and significantly fewer in the Parallelogram 2 enclosure, independent-samples t-test, t(13) = 5.3, p < .001. Furthermore, responding did not differ from chance in the Rectangle enclosure, independent-samples t-test, t(13) = .59, p = .57. These results suggest that in the absence of surface features and beacons, responding depended only upon local geometric cues. However, the presence of beacons facilitated the use of global geometric cues without hindering the use of local geometric cues.

2.3.2. Surface feature: Walls

There was a main effect of Enclosure Type, F(3, 78) = 9.7, p < .001. However, the effect of Beacon Status, F(1, 26) = 1.6, p = .22, and the Enclosure Type × Beacon Status interaction, F(3, 78) = 1.41, p = .25, were not significant. The effect of Enclosure Type was due to significantly fewer geometrically-correct responses in the Parallelogram 2 enclosure than in the other three enclosures, ps < .01. Additionally, the Beams-Present group made significantly more geometrically-correct responses than expected by chance in the Trapezoid, Rectangle, and Parallelogram 1 enclosures, independent-samples t-tests, t(13) > 2.19, ps < .05, but not in the Parallelogram 2 enclosure, independent-samples t-test, t(13) = .23, p > .82. In contrast, the Beams-Absent group made significantly more geometrically-correct responses than expected by chance in the Parallelogram 1 enclosure, independent-samples t-test, t(13) = 5.78, p < .001, but did not differ from chance in the Trapezoid, Rectangle, or Parallelogram 2 enclosures, independent-samples t-tests, t(13) < 2.01, ps > .06. These results suggest that in the presence of surface features bound to the walls near the goal location, responding depended primarily on local geometric cues. The beacons, however, facilitated the use of global geometric cues without hindering the use of local geometric cues.

2.3.3. Surface feature: Floor

There was a main effect of Enclosure Type, F(3, 78) = 5.76, p = .001, a main effect of Beacon Status, F(1, 26) = 6.13, p = .02, but the Enclosure Type × Beacon Status interaction was not significant, F(3, 78) = .34, p = .8. The effect of Enclosure Type was due to significantly fewer responses in the Parallelogram 2 enclosure than the other three enclosures, ps < .05. The effect of Beacon Status was due to the Beams-Absent group making significantly more geometrically-correct responses in the Trapezoid, Rectangle and Parallelogram 1 enclosures than the Beacons-Present group, independent-samples t-tests, t(13) > 13.65, ps < .001. Additionally, the Beacons-Present group made significantly more geometrically-correct responses than expected by chance in the Rectangle enclosure, independent-samples t-test, t(13) = 3.18, p < .01, but not in the Trapezoid, Parallelogram 1, and Parallelogram 2 enclosures, independent-samples t-tests, t(13) < 1.95, p > .07. In contrast, the Beacons-Absent group made significantly more geometrically-correct responses than expected by chance in the Trapezoid, Rectangle, and Parallelogram 1 enclosures, independent-samples t-tests, t(13) > 9.81, ps < .001, but not in the Parallelogram 2 enclosure, t(13) = 1.09, p = .3. These results suggest that the line surface feature bound to the floor of the enclosure facilitated the use of global geometric cues, but did not hinder the use of local geometric cues (i.e., at chance in the Parallelogram 2 enclosure). The presence of beacons appears to have reduced the effect of the Floor surface feature without interrupting the use of global and local geometric cues.

2.3.4. Surface feature: Both

There was no effect of Enclosure Type, F(3, 78) = 1.11, p = .35, or Beacon Status, F(1, 26) = 1.95, p = .18, and no interaction, F(3, 78) = .41, p = .74. However, the Beacons-Present group made significantly more geometrically-correct responses than expected by chance in the Trapezoid, Rectangle, and Parallelogram 1 enclosures, t(13) > 2.34, ps < .05, but not in the Parallelogram 2 enclosure, t(13) = 1.95, p = .07. In contrast, the Beacons-Absent group did not significantly differ from chance in any of the testing enclosures, t(13) < 1.75, ps > .1. These results suggest that the combination of wall and floor surface features hindered the use of local and global geometric cues (i.e., at chance in the Parallelogram 1 enclosure). The presence of beacons, however, appears to have facilitated the use of global and local geometric cues.

3. Discussion

The presence of the beacons during training facilitated acquisition of the task relative to the absence of the beacons. All Beacons-Present groups acquired the task at an equivalent rate and to an equivalently high level of accuracy, regardless of the presence or absence any surface features. In the absence of beacons, the surface features influenced acquisition of the task. The darker-walls surface feature facilitated acquisition to the same extent as the presence of beacons. Such a result suggests that surface features tied to the walls of the enclosure at the goal location may have functioned like beacons. However, acquisition in the absence of wall-surface features (i.e., None and Floor) progressed more
slowly and the asymptote of the acquisition curves was lower. These results suggest, perhaps not surprisingly, that the task was relatively more difficult to acquire in the absence of disambiguating cues (i.e., beacons, shaded walls). Importantly, all groups reliably selected the correct corner more often than expected by chance for the last three blocks of training.

The distribution of responses in the trapezoid test enclosure (see Fig. 3, right panels), in which the surface features and unique beacons were absent, is suggestive of the relative dependence on global and local geometric cues. For example, participants trained in the absence of surface features and beacons (i.e., Surface Feature: None, Beacons-Absent), allocated the majority of responses to the corners with consistent local-geometric cues (i.e., top-right and bottom-right). In contrast, participants trained in the absence of surface features but with beacons present (i.e., Surface Feature: None, Beacons-Present), allocated the majority of responses to the corners that were consistent with global-geometric cues (i.e., top-right and bottom-left). That is, the presence of beacons during training appears to have shifted dependence from local to global cues in the absence of surface features.

The testing enclosures were selected to assess dependence on global-geometric cues in isolation (the Rectangle enclosure), in alignment with local-geometric cues (the Parallelogram 1 enclosure) and in conflict with local-geometric cues (the Parallelogram 2 enclosure). For example (see Fig. 5), participants trained in the absence of surface features and beacons (i.e., Surface Feature: None, Beacons-Absent) responded to the geometrically-correct locations as often as would be expected by chance in the Rectangle enclosure and significantly less than would be expected by chance in the Parallelogram 2 enclosure. That is, consistent with the response distribution in the trapezoid test enclosure, participants’ responding appears to depend on local geometric cues. In contrast, participants trained in the absence of surface features but with beacons present (i.e., Surface Feature: None, Beacons-Present) responded to the geometrically-correct locations more often that would be expected by chance in the Rectangle enclosure and as often as would be expected by chance in the Parallelogram 2 enclosure. That is, consistent with the response distribution in the trapezoid test enclosure, the presence of beacons during training appears to have facilitated the use of global cues. These results are consistent with previous research which has shown that a rectangular arrangement of discrete objects is sufficient to produce reliance on global geometric cues (e.g., Gibson et al., 2007; Pechcia and Vallortigara, 2012; Sutton et al., 2012). However, the at-chance performance of the Beacons-Present group in the Parallelogram 2 enclosure suggests that local-geometric cues continued to influence responding. That is, responding depended on both global- and local-geometric cues in the presence of beacons.

Overall, testing results suggest that the presence of beacons and surface features during training differentially influenced the use of global and local geometric cues (refer to Table 2). When beacons were present during training, participants used both global and local geometric cues regardless of the Surface-Feature condition. That is, participants responded to the geometrically-correct location greater than would be expected by chance in the Rectangle enclosure, in which only global geometric cues were available, and they responded at chance in the Parallelogram 2 enclosure, in which global and local geometric cues were misaligned.

When beacons were absent during training, the surface features influenced the use of global and local geometric cues (refer to Table 2). In the absence of any surface features, participants used only the local geometric cues, as evidenced by at-chance responding in the Rectangle enclosure and below-chance responding in the Parallelogram 2 enclosure. In the presence of wall surface features, participants also only used local geometric cues, as evidenced by at-chance responding in the Rectangle enclosure and a trend toward below-chance responding in the Parallelogram 2 enclosure. In the presence of the floor surface feature, participants used global and local geometric cues, as evidenced by above-chance responding in the Rectangle enclosure and at-chance responding in the Parallelogram 2 enclosure. Lastly, in the presence of both the wall and floor surface textures, participants did not use global or local geometric cues, as evidenced by at-chance responding in all test enclosures—including the Parallelogram 1 enclosure in which global and local geometric cues were aligned.

Collectively, it appears that the local geometric cues in the enclosure are used in the absence of any other orientation cues. Surface features applied to the walls of the enclosure appear to facilitate acquisition but not influence the use of local geometric cues, whereas a line applied to the floor which corresponds to the major principal axis of the enclosure appears to facilitate the use of global geometric cues without hindering the use of local geometric cues. The presence of multiple surface features, however, appears to hinder the use of geometric cues. Finally, the presence of beacons in each corner of the enclosure, regardless of any surface features that may be present, appears to facilitate the use of global geometric cues.

The current results are consistent with previous research indicating the use of both global and local geometric cues for reorientation (Bodily et al., 2011; Lubyk et al., 2012) and extend these findings by examining the roles of beacons and surface features, separately and combined, on the use of geometric cues. Specifically, the current results illuminate some subtle nuances regarding the roles of beacons and surface features on the use of global and local geometric cues. Primarily, they indicate that the influence of beacons and surface features are not functionally equivalent. As result, we believe these results have implications for terminology related to non-geometric cues. Fundamentally, we suggest that, like a distinction between global and local geometric cues, distinctions must be made between surface features and beacon non-geometric cues. Only then will future research be able to delineate the conditions under which various spatial cues are utilized for reorientation.

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