The Use of Categorical Features in Adult Spatial Reorientation

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Abstract

Children often fail to use informative non-geometric features to recover orientation in cases where adults succeed. The present work demonstrates that adults can also fail to use distinguishing information if that information is not encoded categorically. Adults were shown an object being hidden in a corner of a rectangular room rendered with an immersive virtual display. They were then disoriented and asked to locate the object. The short walls of the room were discriminably different colors so that they could be used to uniquely specify the orientation of the viewer with respect to the enclosure. When the colors were members of different major color categories, participants were more likely to succeed in the task. In fact, participants succeeded in the task if and only if they encoded the color difference lexically. This indicates that categorical encoding plays an important part in reorienting with non-geometric features and implicates language as a default medium of categorical encoding.

Keywords: Spatial Memory; Navigation; Language; Reorientation

Introduction

All mobile animals appear to possess mechanisms for reestablishing orientation in a familiar environment after disorientation (Cheng & Newcombe 2005). To investigate these mechanisms, researchers commonly employ a variant of the disorientation procedure. In this task, the animal or human participant observes while an object is hidden in an enclosed space. The animal is then disoriented before being allowed to search for the object. By manipulating the environmental cues available in the enclosure, a researcher can identify the allocentric features used in this process. For instance, Cheng and Gallistel determined that rats can reorient using the relative lengths of adjacent walls in a rectangular enclosure. If food is concealed in a corner of the room (e.g., where a long wall is to the left of the short wall), a disoriented rat will search both in the correct corner and the opposite corner, which is geometrically equivalent (Cheng & Gallistel 1984; Cheng 1986). Subsequent research has established that children and many animals perform similarly (see Ratcliff & Newcombe 2008 for a review). Children have also been shown to use the geometric arrangement of extended surfaces when reorienting in an enclosure shaped like an isosceles triangle (Huttenlocher & Vasilyeva 2003), a rhombus (Hupbach & Nadel 2005), and an octagon (Newcombe & Ratcliff 2006).

It has been proposed that geometric information might play a privileged role in guiding reorientation. Gallistel (1990) points out that, in a natural environment, the geometric layout of a landscape is relatively stable. Nongeometric features such as the colors or textures of landmarks are subject to seasonal and other types of variation. For this reason, organisms may have evolved to be especially sensitive to geometric information when reorienting. Support for the special status of geometric cues comes from the fact that non-geometric information is often ignored in this task. For instance, Cheng found that rats searched rotationally equivalent corners of a rectangular room even when provided with a landmark feature, such as a differently colored wall, that could specify the correct location (1986). Children up to five years-old also fail to use nongeometric information in certain circumstances (Hermer & Spelke 1994, 1996; Hermer-Velasquez, et al 2001; Learmonth, Nadel & Newcombe 2002). These results have been adduced as support for an encapsulated module that considers only geometric information in reorienting (Cheng 1986; Gallistel 1990; Hermer & Spelke 1986; Wang & Spelke, 2002, 2003)

Despite its theoretical appeal, recent results cast doubt on the existence of a purely geometric module for reorienting. One issue is that the size of the enclosure influences sensitivity to nongeometric information. For instance children will ignore featural information if a rectangular enclosure is four feet by six feet, but become more likely to use featural information if the dimensions increase to eight feet by twelve feet (Learmonth, Newcombe & Huttenlocher, 2001; Learmonth, Nadel & Newcombe 2002). This demonstrates that nongeometric information can be used in certain ordinary environments, reducing somewhat the scope of a potential module.

Another challenge for a modular architecture is that some types of non-geometric information can be used by children as young as 18-24 months. Huttenlocher and Laurenco (2007) used a square enclosure with circles on the walls. Opposite walls had identically sized circles, but the circles for adjacent walls differed in size. Though all corners were geometrically equivalent, toddlers reliably selected the correct corner or its rotational equivalent. Subsequent studies seem to indicate that children also exhibit sensitivity to non-geometric cues when adjacent walls have lines of different orientation and when adjacent walls have different shades of grey (Laurenco & Addy 2008). The fact that non-geometric features can be used in such circumstances is difficult to reconcile with an encapsulated geometric module.

Intriguingly, toddlers at the same age failed to identify the correct corners of a square room when adjacent walls were different colors, such as blue and red (Huttenlocher & Laurenco 2007). Taken together, these results suggest that children may be able to map features onto spatial locations when the features take on different values along a scale (e.g., size, slope, luminance), but not when the features are most naturally coded into discrete categories (e.g., colors). Huttenlocher and Laurenco hypothesize that when the available features can be ordered on a continuum, they can be more easily mapped onto the continuum of relational space than when these features consist of distinct, unordered, categorical properties.

While the Huttenlocher and Laurenco hypothesis provides a potential explanation for why children sometimes fail to use non-geometric information, it does not explain how adults come to successfully incorporate such information (e.g., Hermer-Velasquez, Spelke, & Katsnelson 1999; Ratcliff & Newcombe 2008). Complete understanding of human reorientation abilities requires examination of the mature system. One possibility is that adults use of non-geometric information hinges on the ability to encode and maintain categorical properties. The developmental shift from reliance on continuous properties to reliance on categorical encoding is likely reflected in, and possibly aided by, the mastery of linguistic labels. The current study explores these ideas by comparing adult reorientation in a case where a categorical contrast was required to specify a spatial location versus a case where a non-categorical contrast was required. The results indicate that categorical encoding is necessary for success. Below we present the experiment followed by arguments that linguistic labels provide a default representational code which underlies adult categorical encoding when reorienting.

Experiment

To test the hypothesis that categorical encoding contributes to adult reorienting behavior, we adapted the reorienting task of Cheng and Gallistel (1984). Participants were disoriented in a virtual rectangular room for which the long walls were white and the short walls were colored. The colors on the short walls were different so that their spatial arrangement could be used to uniquely determine orientation in the room. Color pairs either came from the same color category (blue) or spanned a color boundary (blue-green). Importantly, each color pair was easily discriminated.

Note that categorically encoding the two colors is not a logical prerequisite to recovering orientation in this environment. It is possible to encode them comparatively along a continuous dimension (e.g., $wall_1$ is darker/purpler/more-prototypically-blue than $wall_2$). The hypothesis under investigation here is that categorization is the most natural means of solving the task for adults.

If adults solve the reorientation task by encoding this relationship categorically, then cross-category color differences should be more useful than within-category differences. If instead categorical encoding does not contribute to reorientation, participants should have similar success rates in both conditions.

Methods

Participants

Thirty-two Swarthmore undergraduates (12 male) completed the experiment. They were paid for their participation. They were all native speakers of English and had normal, or corrected to normal, visual acuity. One additional participant did not complete the experiment.

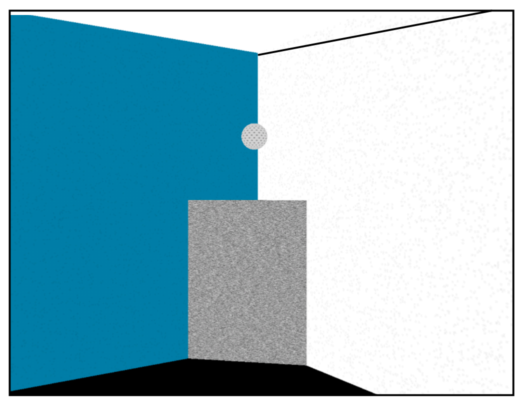

Figure 1: Participants' view of a corner of the room including target.

Virtual Environment

The environment was a rectangular room (12 x 8 ft and 7.5 ft high), that had two long walls which were white and two shorter walls whose colors were determined by the condition the participant was in. A virtual ball (.2 m in diameter) moved around the room and disappeared behind one of four identical textured panels in the corners of the room. During the disorientation phase of the experiment, a textured cylinder (2 m in diameter) dropped from the virtual ceiling and rotated around the participant. An image of one corner of the room, with the ball visible is shown in Figure 1.

Color Selection and Rendering

The colors were matched in lightness and saturation, and equally separated along the hue dimension of Munsell color space –a space designed to represent perceptual differences (Munsell 1912). Three Munsell colors, 7.5 BG 6/8 (10 113 114), 5B 6/8 (10 108 15), and 2.5 PB 6/8 (42 97 165) were selected for the walls. The Munsell groupings and intuitions among the experimenters concurred that the first color was most naturally labeled "green" whereas the latter two were most naturally labeled "blue." The head-mounted virtual display was calibrated using EasyRGB.com. This allowed us to identify the appropriate RGB values of the target colors for our display. Those RGB values, converted to linear proportions were used in the OpenGL specification of the colors of the walls to be shown in the display. Lighting was disabled in the OpenGL set-up so that the intended colors would be presented without shading, which would have caused the color to vary along the walls according to distance and angle from the light source. Note that this kind of color control is not easily achieved in an actual environment.

For the within-category group of participants, the walls were 5B 6/8 and 2.5PB 6/8 (both blue). For the cross-category group of participants, the two colors were 7.5BG 6/8 and 5B 6/8 (green and blue respectively). The two sets of colors were equally far apart in Munsell space. To ensure that both color sets could be easily discriminated, an additional set of participants who did not perform the main experiment was enlisted in a categorization task. Half of the participants were assigned to the within category pairing, and half were assigned to the between category pairing. Individuals wore the head-mounted display and were shown one colored wall or the other on each of 100 trials. They were asked to classify each color as either "A" or "B." Feedback was given after each response. With the exception of the first trial, which required the participant to learn which color was "A" and which was "B," performance was essentially flawless for both color sets. When asked afterward what the colors had been, people in the within-category group generally used multi-morphemic descriptors (e.g., "purply-blue" and "turquoisy-blue" or "greeny-blue" and "dark blue"), whereas those in the cross-category task systematically used the mono-morphemic color names "blue" and "green."

Design and Procedure

Participants for the main experiment were assigned quasi-randomly to one of two conditions. In one condition the two short walls of the virtual room were from different color categories. In the other condition the two walls, though different in color, would both be described as blue. These color differences were intended to operationalize linguistically-distinct and linguistically non-distinct color categories. The random assignment was done by computer so that the experimenter remained blind to condition. Separate assignments were conducted for male and female participants to ensure that the conditions were balanced for gender (i.e., six males and ten females were in each condition).

The ball was depicted as traveling along the walls of the room starting from the middle of one of the white walls. There were 16 different paths (series of path segments) that the ball could travel around the virtual environment before disappearing behind one of the textured panels in each corner of the room. Each path included both of the colored walls. The ball traveled one of these paths per trial, so that each participant viewed all 16 possible paths in random order. Each corner was used as a hiding place four times. Initial room orientation was random with respect to the physical space. At the beginning of the search phase, the participants were always oriented by the experimenter in the same direction in the physical room, and the virtual room was oriented so that they were directly facing one or the other of the two colored walls, at random. Participants then oriented themselves toward the corner where they believed the ball had been hidden and pressed a button to indicate their response. Both their orientation and the time of response were recorded.

A debriefing questionnaire at the end of the experiment was used to gather reports concerning how successful participants thought they had been, what conscious strategies they had adopted, the perceived shape of the room, what colors they had thought the walls were, what they thought the experiment was investigating, and whether they had anomalous color perception.[1]

Apparatus

The experiment was conducted in an immersive virtual environment using an nVis head-mounted display (HMD). The resolution of the HMD was 1280 x 1024 @ 60 Hz, with a field of view of 39 x 51 degrees of visual angle. The display was in stereo and the software used the interpupillary distance of each participant (IPD, measured with an electronic PD meter) to specify the scene perspective. A HiBall headtracker provided position and orientation information (6 DOF) with sub-mm precision at 120 Hz. The system had very a low effective lag (about 35-50 ms). Participants were seated in a heavy chair that allowed them to easily rotate to face any direction in the virtual environment. The chair allowed us to re-orient participants during the storage phase of each trial. Earplugs (NR 29) were worn to reduce auditory localization information from the physical environment. Participants indicated their response using a radio mouse.

Results

Participants in each condition reliably selected the correct corner or the geometrically equivalent corner more often than chance (within-category: 65.6%, *SE*=3.4%, $t(15)=4.63$,

[1] Two male participants, one from each condition, reported deficient color perception. The analyses below include their data because they each performed well above chance in the main task, and because the patterns of significant effects were not affected by the omission of their data.

$p < .001$; cross-category: 71.5%, *SE*=2.1%, $t(15)=10.46$, $p < .001$). This demonstrates that both groups were sensitive to the spatial layout of virtual environment while reorienting.[2] As predicted by the categorical encoding hypothesis, success in locating the correct corner was reliably greater when the wall colors crossed a color boundary (55.1 ± 4.8%) than when they did not (42.6 ± 4.3%), $t(30) = 1.948$, $p < .05$. This demonstrates that participants were more likely to succeed at the task when the available features were easier to distinguish categorically. Success rate was not influenced by the sex of the participants.

It is possible that the benefit for the cross-category group arose because the color distinction was easier to spontaneously encode categorically from the first trial of the experiment. Alternatively it might have resulted because the cross-categorical distinction was easier to acquire over the course of the experiment. To compare these possibilities, we compared performance on just the first trial. Even for this trial, the cross-category group showed marginally higher performance than the within-category group ($t(30) = 1.42$, $p = .08$). Performance by condition across each four trial block of the experiment is depicted in Figure 2. That we see the same general patterns from early in the experiment indicates that the cross-category distinction was easier to spontaneously classify. However, this does not rule out the possibility that the cross-boundary distinction was also easier to learn over the course of the experiment.

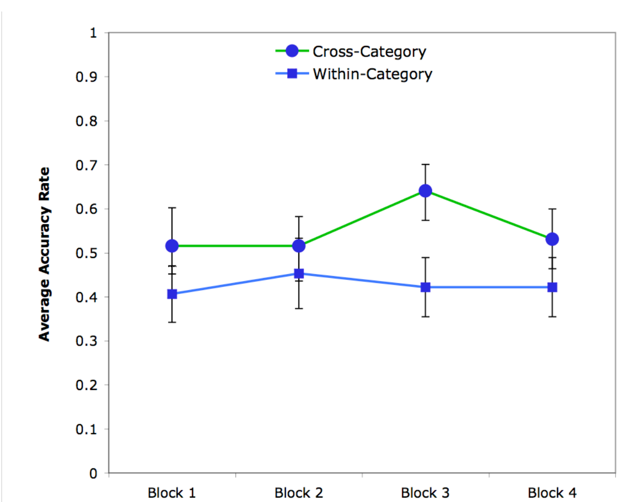

Figure 2: Success rate by condition by block (error bars depict standard errors of the means)

[2] Responses respected room geometry 68.6% of the time. This rate is lower than that reported in earlier work with adults, which hovers around 80%. The difference may reflect difficulty with recovering spatial information in the virtual environment, possibly due to the limited field of view and the fact that the room was only viewed while seated in a chair at the center. Proactive interference from earlier trials may have also degraded performance: we included 16 trials where previous work with adults has used four or fewer (Hermer-Velasquez et al 1999; Ratcliff & Newcombe 2008).

A second way of quantifying success is by determining whether participants accurately described the correct strategy in the debriefing. That is, did the participant report using the spatial arrangement of differentially colored landmarks. Whereas 12 of the 16 participants in the cross-category condition described using the correct strategy, only 5 of 16 in the within-category condition did, $X^2(1) = 6.149$, $p = .0131$. Indeed, 6 participants in the cross-category condition reported arriving at the correct strategy on the very first trial, compared to only 1 in the within-category condition, $X^2(1) = 4.571$, $p = .0325$. The validity of these self-reports of strategy are supported by the performance data presented in Figure 3, where participants are divided into groups of those who reported immediately adopting the strategy, those who said they adopted it eventually, but not immediately, and those who did not discover the successful strategy.

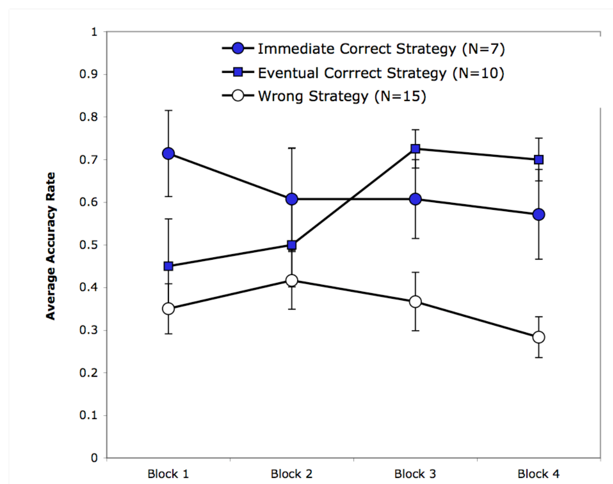

Figure 3: Success rate by self-report of correct strategy use.

Because individuals' color boundaries may have been variable, and to establish whether success was correlated with the availability of a major color category, we analyzed the color terms participants applied when asked to draw the room and label the color of each wall. Whereas 8 of the 12 participants who identified the correct strategy in the cross-boundary condition used mono-morphemic terms for both wall colors (either "green" or "teal" and "blue"), only 1 of the 5 successful participants in the within-category condition did so. Thus, people who differentiated between the colors of the two walls were far more likely to use at least one multi-morphemic color term if the wall colors were intended to be within a linguistic color category, as was our intent, $X^2(1) = 4.571$, $p = .0196$.

Though the availability of a basic color distinction is likely to facilitate categorical encoding, it is clearly possible to categorically encode the color distinction even when this basic category is not available (e.g., "purply-blue" vs. "greeny-blue"). Strikingly, all and only the participants who reported the correct strategy also spontaneously provided different color labels in debriefing. To delve more deeply into this issue, and to further ensure that strategic self-report was an accurate indicator of success, we separately analyzed the performance of those individuals who assigned multiple color labels (N=17) and those who did not (N=15). Those who assigned multiple color labels to the walls identified the correct corner 60.7 ± 3.7% of the time and the rotationally symmetric corner 10.3 ± 3.6% of the time. This ratio was significantly higher than chance ($t(16) = 7.91$, $p < .001$). For individuals who did not assign different color the correct corner was selected 35.4 ± 3.3% and the symmetric corner 30.4 ± 2.9%. This was not reliably better than chance ($t(14) < 1$). Thus there was no evidence that individuals who did not assign distinct color categories unconsciously followed an appropriate strategy.

Discussion

The present experiment provides strong evidence that adults rely on categorical properties for recalling the spatial orientation of a room. Individuals were more likely to exploit the arrangement of two distinctly colored walls when the colors were tokens of different basic categories than when they came from the same category. This was true despite the fact that the within-category colors were highly discriminable. Moreover, we found participants in the within-category condition successfully used the color distinction only when they explicitly coded the colors with different labels. Analogously, participants in the between-category condition failed to reorient only when they coded the colors identically.

Why is categorical encoding naturally employed in this task? Encoding a potentially infinite continua with a finite set of discrete categories likely eases the representational burden in memory. Note that our version of the reorientation task may place a higher demand on memory because the two colored walls cannot be viewed simultaneously. As a result comparing the two colors has to be performed successively. Though it may be representationally more efficient to employ categorical codes in this process, the categorical representation abstracts away from the perceptual stimulus. This eliminates within category differences and enhances between category differences. If the reorienting task required attending to differences between adjacently colored walls, it would likely reduce the burden on memory, and hence reduce reliance on categorical coding.

The Role of Language

It should be emphasized that the use of linguistic labels did not have to correlate perfectly with task success. For one thing, a relative representation of the hues would have been sufficient for reestablishing spatial heading.[3] For another, it would have been logically possible for participants to encode the two colors categorically without using *linguistic* categories. Namely, each wall might be classified as a different category of blue without using a linguistic label to reflect that difference.

It is possible that the availability of linguistic labels enabled the colors to be coded categorically. Alternatively, the categorical distinction may have caused a divergence in linguistic forms. The present work does not settle this issue. However, a number of considerations point to language as a representational medium that supports the flexible use of categorical information.

First, language is an a priori reasonable medium for encoding categorical information because categorical distinctions typically correlate with lexical distinctions. Further, there is a broad consensus that linguistic labels can have cognitive effects. For instance, a linguistic label can both draw an individuals' attention to a particular conceptual distinction, as well as provide an additional code for maintaining a concept in memory (see e.g., Gentner & Goldin-Meadow 2003 and Pinker 1994, 2007). It is possible that adults have come to depend on language in tasks where a categorical distinction must be coordinated with other information in memory (here spatial locations).

Second, a number of empirical results support a direct role of language in reorienting specifically. Hermer-Vazquez, Moffet, and Munkholm (2001) found a correlation between the age at which children begin to reorient according to a non-geometric feature (a colored wall) and a linguistic milestone –the age at which they begin to spontaneously produce the spatial terms "left" and "right" in referential descriptions. This raises the possibility that linguisitic development underlies task success. More direct evidence for the role of language in reorienting was reported by Hermer-Vazquez, Spelke, and Katsnelson (1999). They asked adults to perform a secondary distracter task for the duration of the hiding, disorienting, and search phases of the reorientation task. When the secondary task was a verbal-shadowing task, participants ignored non-geometric features and relied solely on the geometric layout. In contrast when the secondary task was a non-verbal rhythm-shadowing task, participants reoriented successfully. This indicates that the disruption of verbal abilities impaired the use of non-geometric features to specify a spatial location.[4]

[3] It is worth noting than no participant generated color labels containing morphemes with comparative properties (e.g., the "-er" suffix or the adverb "more").

[4] Ratcliff and Newcombe (2008) dispute that language plays a role in human reorienting based on the fact that secondary spatial tasks can also impair performance (see also Hupbach, Hardt, Nadel & Bohbot 2007). However, two considerations weaken this argument. First, it may be that spatial distractor tasks disrupt the representation of space necessary for reorienting. Thus a spatial distractor task has little bearing on whether a verbal code is also used in the task. Second, their distractor tasks may have had a verbal component. Ratcliff and Newcombe used the Brooks letter-tracing task with verbal responses. The verbal response required for this task has been found to interfere with verbal cognition. Indeed, this was one of Brooks' central results (1968).

Importantly, the question of whether adults' use of categorical information is mediated in part by language is independent of the question of whether or not reorienting relies on a modular architecture (geometric or otherwise) and whether such a module is unique to humans. Though some investigators have argued that language is the primary representational system medium for combining information from encapsulated cognitive domains (Carruthers 1998; Spelke 2003), we believe that the available evidence is also consistent with a more modest proposal. Namely that language provides a default cognitive technology that can aid memory and guide attention. Reliance on linguistic codes may be more acute when tasks become more difficult, as when information from multiple representational formats must be combined. This does not mean that language is the sole, or even primary, means for conceptual combination.

Conclusion

We have presented evidence that the adult reorientation in a familiar environment relies on categorical encoding of non-geometric features. The extent to which this ability is enabled by linguistic codes and the mechanisms by which children overcome an early insensitivity to categorical features are open issues to be addressed in future research.

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