



## Short communication

## Encoding of relative enclosure size in a dynamic three-dimensional virtual environment by humans

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## ABSTRACT

Human participants searched in a dynamic three-dimensional virtual-environment rectangular enclosure for a distinctly colored bin located in one of the four corners. During test trials, all bins were rendered identical in color, and the shape of the rectangular search space either remained the same or was modified to a relatively sized contracted rectangle, an expanded rectangle, or a square. Participants made one choice response during test trials. In the rectangular enclosures, more of participants' choice responses were allocated to the geometrically correct corners than to the geometrically incorrect corners. In the square enclosure, participants' choice responses were allocated equivalently to each of the four corners. Results replicate previous enclosure size studies demonstrating encoding of enclosure geometry with human and non-human animal subjects conducted in real environments and extend these results to include encoding of relative enclosure geometry. Results are discussed with respect to theoretical accounts of geometry learning.

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Navigating an environment requires the acquisition and maintenance of a trajectory from location to location. Fundamental to this process is an estimation of orientation and position with respect to the environment (Gallistel, 1990). Mobile organisms appear to accomplish this task through multiple cues such as geomagnetic fields, celestial bodies, landmarks, or vestibular feedback (for a review, see Healy, 1998). Oftentimes, a distinction is made between features (objects in the environment) and geometry (shape of an enclosure) [for reviews, see Cheng and Newcombe, 2005; Spetch and Kelly, 2006].

Orientation via enclosure geometry was first demonstrated by Cheng (1986). Disoriented rats trained in a rectangular enclosure with distinct cues at each corner allocated equivalent responses to the correct corner and the rotationally equivalent corner when distinct cues were removed or rendered identical. Moreover, responses to these geometrically correct corners were significantly more than those to the geometrically incorrect corners. Replications of this *rotational error* phenomenon in enclosed search spaces have been obtained with various vertebrates including chickens (Vallortigara et al., 1990), pigeons (Kelly et al., 1998), fish (Sovrano et al., 2003), and humans (Hermer and Spelke, 1994) and recently with invertebrates (ants: Wystrach and Beugnon, 2009).

Although it has been suggested that geometry extracted from enclosures is learned incidentally by a dedicated geometric module (Cheng, 1986; Gallistel, 1990; for a review, see Cheng and Newcombe, 2005), emerging evidence suggests that geometry may be learned associatively like that of other environmental cues (for a review, see Cheng, 2008). For example, Miller and Shettleworth (2007) have proposed an associative-based account of geometry learning that deconstructs geometry of an enclosure into distinct cues (e.g., wall lengths, angles, sense) – each capable of acquiring independent associative strengths. Such an associative-based account seems to explain many observed phenomena in enclosure search tasks such as differential influences (i.e., cue competition or lack thereof) of features and/or geometry. Moreover, Miller (2009) has extended this associative-based account to explain the differential influences of features and/or differently sized enclosures [as has been shown in several species: chicks (Chiandetti et al., 2007; Vallortigara et al., 2005), fish (Sovrano et al., 2005, 2007), and humans (Learmonth et al., 2002)]. This associative-based account explains greater relative behavioral control by geometry in small enclosures and by features in large enclosures through differential allocation of amounts of associative strength to features and/or geometry dependent on enclosure size.

Such an associative-based account of geometry learning appears consistent with recent human research utilizing dynamic three-dimensional (3D) virtual environments to study the interactions of enclosure size/shape and features (Alexander et al., 2009; Wilson and Alexander, 2008). Despite increased use of dynamic 3D virtual

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environments in spatial research (for a review, see Kelly and Gibson, 2007), direct examination of the metric used to encode geometry (i.e., absolute or relative) has not been conducted in dynamic 3D virtual environments (however, for static 3D virtual environments, see Kelly and Bischof, 2005, 2008). In addition, in spite of the promising aforementioned associative-based account of geometry learning, explaining behavioral control by geometry when enclosure size is manipulated between training and testing seems problematic for such an account because the enclosure size is not considered as an element (Miller, 2009). As several species have now been shown to differentially use features and geometry in small and large enclosures, this is an important aspect that must be addressed by associative-based accounts of geometry learning.

The purpose of the present experiment was two-fold: first, we conducted a partial conceptual replication of Cheng (1986) with humans in dynamic 3D virtual enclosures to determine the validity of virtual environments as a paradigm for studying human spatial orientation; second, we presented participants with enclosures that changed in relative size from training to testing to inform theoretical accounts of geometry learning. The design follows that of Kelly and Spetch (2001) who demonstrated that pigeons encoded relative geometry when the enclosure was manipulated in relative size from training to testing.

In the present experiment, participants searched in a dynamic 3D virtual-environment rectangular enclosure for a distinctly colored bin located in one of the four corners. During test trials, all bins were identical in color, and the shape of the rectangular search space either remained the same or was modified to a relatively sized

contracted rectangle, an expanded rectangle, or a square. If participants encode enclosure geometry of the virtual training space, and this information is relative in nature, they should allocate more responses to the geometrically correct than to the geometrically incorrect corners during manipulations of rectangular enclosure size. In contrast, if this information is absolute in nature, their allocation of responses should show the exact opposite result during these manipulations of rectangular enclosure size (i.e., more responses to the geometrically incorrect than to the geometrically correct corners). The square enclosure should serve as a control (i.e., lack of informative enclosure geometry), and participants should allocate responses equally to each of the four corners.

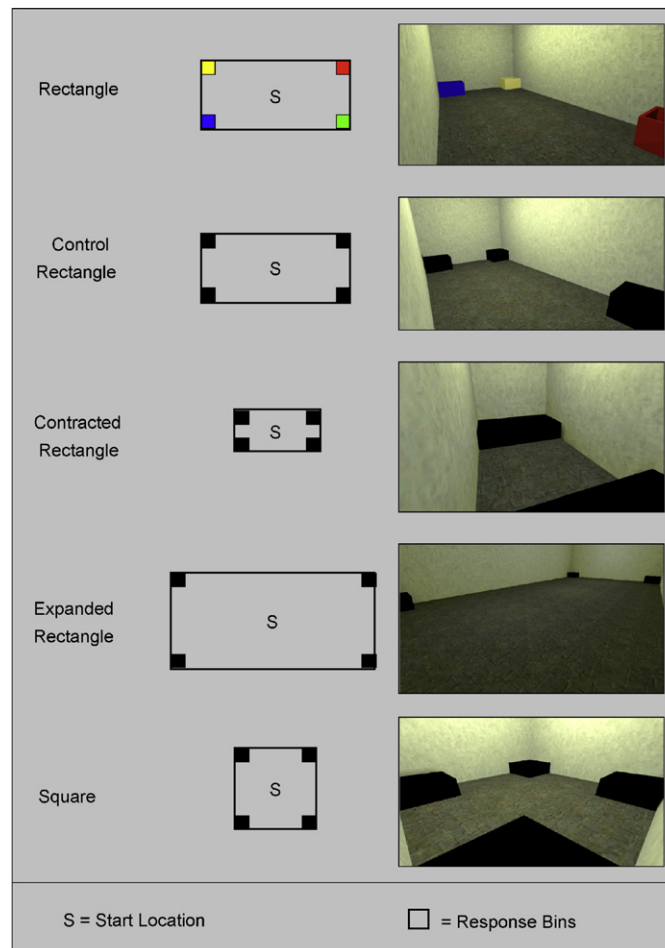
## 1. Method

### 1.1. Participants

Twenty Armstrong Atlantic State University undergraduate students (4 males and 16 females) served as participants. Participants received extra class credit.

### 1.2. Apparatus

An interactive, dynamic 3D virtual environment was constructed and rendered using Valve Hammer Editor and run on the Half-Life Team Fortress Classic platform. A personal computer, 19-inch flat-screen liquid crystal display (LCD) monitor, optical mouse, keyboard, and speakers served as the interface with the virtual envi-



**Fig. 1.** Labels (left column), schematics (middle column) and images from the first-person perspective (right column) of virtual environment search spaces. Filled squares mark response bins. For illustrative purposes, the S marks the position where participants entered the virtual enclosures for all Training and Testing trials.

ronment. The monitor (1152 × 864 pixels) provided a first-person perspective of the virtual environment (see right column, Fig. 1). The arrow keys of the keyboard, the mouse, and the left mouse button navigated 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 length × width × height and measured in virtual units (vu). Five virtual enclosures were created (see Fig. 1): rectangle (568 × 284 × 281 vu), control rectangle (568 × 284 × 281 vu), contracted rectangle (284 × 142 × 281), expanded rectangle (1236 × 568 × 281), and square (282 × 282 × 281). Each enclosure contained four raised bins (86 × 86 × 38 vu) arranged one in each corner. Bin colors were red, blue, yellow, green, or black depending on trial type (see below). The enclosures were illuminated by a light source centered 64 vu below the ceiling. All surfaces were white in color with the exceptions of the floors (grey) and the ceilings (black).

### 1.4. Procedure

Participants were informed to locate the bin that transported them to the next virtual room and moved via keyboard keys: ↑ (forward), ↓ (backward), ← (left), and → (right). Movement of the mouse changed the view within the environment, and auditory feedback indicated movement (footstep sounds). Participants selected a bin by jumping into it. To jump into a bin, participants simultaneously moved forward (↑) and jumped (left mouse button). Auditory feedback indicated a jump occurred (“huh” sound). Selection of the rewarded bin resulted in auditory feedback (transport sound from Super Mario Bros.™) and a 1 s inter-trial interval (ITI) in which the monitor went black and participants progressed to the next trial. Selection of a non-rewarded bin resulted in different auditory feedback (game over sound from Super Mario Bros.™) and required participants to jump out of the current bin and continue searching.

#### 1.4.1. Training

Training consisted of eight trials. Participants were randomly assigned to one of the four corners which was then designated as the rewarded corner. Gender and number of participants trained at each corner was balanced. Participants started each trial in the center of the rectangle (marked S in Fig. 1). Participants entered the rectangle at random orientations from 0° to 315° in increments of 45°. Each of the four bins was marked in a distinct color: blue, yellow, red, green.

#### 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. Location of the Test trial was randomized within block. For each Test trial, one of four enclosures was presented: control rectangle, contracted rectangle, expanded rectangle, and square. 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 choice during Test trials which resulted in no auditory feedback followed by the 1 s ITI and progression to the next trial. Participants entered all enclosures during Testing in the center of the enclosures (marked S in Fig. 1) at random orientations from 0° to 315° in increments of 45°. All bins were black during Test trials.

## 2. Results and discussion

Fig. 2 (top panel) shows the mean proportion of participants' first choices to the rewarded bin plotted by two-trial blocks for the eight trials of Training. As shown, participants' choices did not differ from chance performance (i.e., 0.25) during Block 1, one-sample  $t$ -test,  $t(19) = 1.0$ ,  $p > .05$ , but rapidly came under control of the rewarded bin. In fact, choices did not differ from perfect performance (i.e., 1.0) by Block 4, one-sample  $t$ -test  $t(19) = -1.37$ ,  $p > .05$ . A one-way repeated measures analysis of variance (ANOVA) on mean proportion of first choices to the rewarded bin with Block (1–4) as a factor revealed a main effect,  $F(3, 57) = 18.89$ ,  $p < .001$ . Post hoc tests revealed Block 1 was significantly different from all other Blocks ( $ps < .01$ ), but Blocks 2–4 were not significantly different

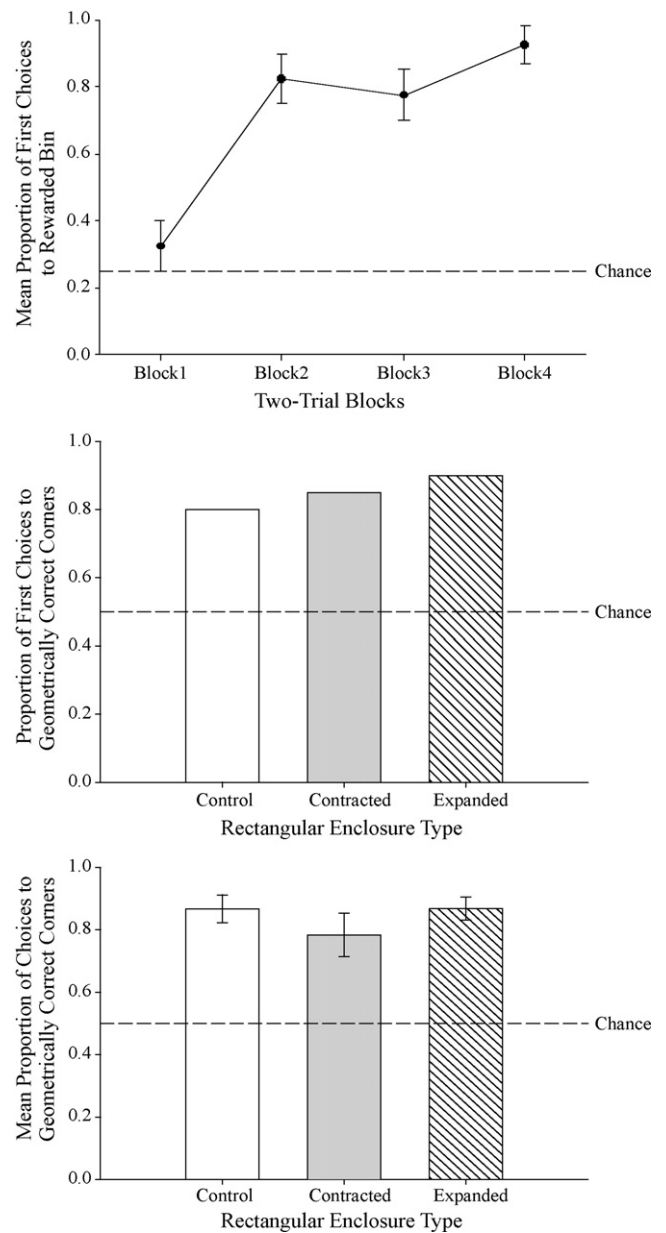


Fig. 2. Top panel. Mean proportion of participants' first choices to the rewarded bin plotted by two-trial blocks for the eight trials of Training. Middle panel. Proportion of participants' first choices during Testing to the geometrically correct corners plotted by rectangular enclosure type. Bottom panel. Mean proportion of choices during Testing collapsed across all three presentations of each rectangular enclosure type to the geometrically correct corners plotted by rectangular enclosure type. Dashed lines represent chance performance. Error bars represent standard errors of the mean.

from each other ( $ps > .05$ ). Additionally, Blocks 2–4 were all significantly greater than chance performance (i.e., 0.25), one-sample  $t$ -tests,  $ts(19) > 6.8$ ,  $ps < .001$ .

Fig. 2 (middle panel) shows the proportion of participants' first choices to the geometrically correct corners plotted by rectangular enclosure type. Despite absence of distinct cues or absence of distinct cues and relative changes to rectangular enclosure size, more proportions of first choices were allocated to the geometrically correct corners than would be expected by chance (i.e., 0.5) for each rectangular enclosure type,  $\chi^2(1, N=20) = 7.2$ ,  $p < .01$ ,  $\chi^2(1, N=20) = 9.8$ ,  $p < .01$ ,  $\chi^2(1, N=20) = 12.8$ ,  $p < .001$ , for control, contracted, and expanded rectangles, respectively. In the absence of distinct cues in the square enclosure, the proportions of first choices were equivalent to each of the four corners (0.25; 0.25; 0.15; 0.35),  $\chi^2(3, N=20) = 1.6$ ,  $p > .05$ .

These effects were also obtained when mean proportions were calculated over repeated presentations of enclosures. Fig. 2 (bottom panel) shows mean proportion of choices collapsed across all three presentations of each rectangular enclosure to the geometrically correct corners plotted by rectangular enclosure type. Despite absence of distinct cues or absence of distinct cues and relative changes to rectangular enclosure size, more mean proportions of choices were allocated to the geometrically correct corners than would be expected by chance (i.e., 0.5) for each rectangular enclosure, one-sample  $t$ -tests,  $t(19) = 8.3$ ,  $p < .001$ ,  $t(19) = 4.1$ ,  $p < .01$ ,  $t(19) = 9.9$ ,  $p < .001$ , for control, contracted, and expanded rectangles, respectively. Additionally, these mean proportions did not differ from each other as confirmed by a one-way repeated measures ANOVA on mean proportion of choices to the geometrically correct corners with Rectangular Enclosure Type (control, contracted, expanded) as a factor which did not reveal an effect,  $F(2, 38) = 1.4$ ,  $p > .05$ . Moreover, mean proportion of choices to the correct and rotationally equivalent corners did not differ from each other for each rectangular enclosure as confirmed by a two-way repeated measures ANOVA on mean proportion of choices with Corner (correct, rotationally equivalent) and Rectangular Enclosure Type (control, contracted, expanded) as factors which did not reveal any significant effects or interaction,  $F_s < 1$ ,  $ps > .05$ . Furthermore, choices to each of these corners for each rectangular enclosure were greater than chance performance (i.e., 0.25), one-tailed, one-sample  $t$ -tests,  $ts(19) > 1.9$ ,  $ps < .05$ . In the absence of distinct cues in the Square enclosure, mean proportion of choices were equivalent to each of the four corners ( $M = 0.25$ ,  $SD = 0.21$ ;  $M = 0.33$ ,  $SD = 0.24$ ;  $M = 0.18$ ,  $SD = 0.20$ ;  $M = 0.23$ ,  $SD = 0.22$ ) as confirmed by a one-way repeated measures ANOVA on mean proportion of choices with Corner (1–4) as a factor which did not reveal an effect,  $F(3, 57) = 1.2$ ,  $p > .05$ . Additionally, these mean proportions did not differ from chance performance (i.e., 0.25) as confirmed by one-sample  $t$ -tests,  $ts(19) < 1.6$ ,  $ps > .05$ .

Results in the present dynamic 3D virtual-environment search task appear consistent with extant human and non-human animal research conducted in real environment enclosures that document the rotational error phenomenon (for a review, see Cheng and Newcombe, 2005) and provide evidence to support the validity of dynamic 3D virtual environment tasks in the study of human spatial orientation. As importantly, present results extend previous research by demonstrating encoding of relative enclosure geometry by humans. Such a result appears inconsistent with current associative-based accounts of geometry learning (e.g., Miller, 2009; Miller and Shettleworth, 2007). Present results suggest that participants may encode (or compute) the ratio of short-to-long wall (i.e., relative metrics). Perhaps this ratio serves a critical role in the sense component of an associative-based account delineated by Miller (2009) and Miller and Shettleworth (2007).

Image matching approaches to understanding geometric encoding account for the use of relative geometry (see, Cheng, 2008).

Specifically, image matching involves reducing the discrepancy between an organism's current retinal image and a representation stored in memory containing a view from the goal location. For example, ants and honeybees appear to search until their current retinal image matches that of an image stored in memory (for reviews, see Cheng, 2000; Collett and Zeil, 1998; see also Cheung et al., 2008; Stürzl et al., 2008). Future research should explore such possibilities using continuous rather than discrete search tasks to inform theories of geometry learning and illuminate how animals orient with respect to their environment.

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