ABSTRACT

TOWARDS A DEFINITION OF INTRINSIC AXES: THE EFFECT OF ORTHOGONALITY AND SYMMETRY ON THE PREFERRED DIRECTION OF SPATIAL MEMORY

by Laurence Richard

Mou, Zhao & McNamara (2007) proposed the “intrinsic model of human spatial memory”, which posits that a viewer’s memory of an array of objects will exhibit a preferred direction that is aligned with an intrinsic axis of the array. They defined intrinsic axes as salient axes created in part by the physical (geometric) properties of the array. To date, these geometric characteristics have received little research attention. We begin such an endeavor by evaluating the role of symmetry and orthogonality (i.e., number of right angles in the studied array of objects) in spatial memory. Results were consistent with greater reliance on egocentric reference frames than is common in the literature. Indeed, for only one array -- a highly orthogonal and symmetric one -- did participants respond non-egocentrically. We suggest that overuse of this array in the literature has led to an overestimation of the importance of allocentricity in spatial memory.

TOWARDS A DEFINITION OF INTRINSIC AXES: THE EFFECT OF ORTHOGONALITY
AND SYMMETRY ON THE PREFERRED DIRECTION OF SPATIAL MEMORY

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Table of Contents

List of tables.....	iii
List of figures.....	iv
Introduction.....	1
Methods.....	6
Participants	6
Materials.....	6
Procedure.....	7
Design and data analysis	8
Results.....	9
Discussion	11
Geometrical features	12
The modal array	12
Egocentricity	13
Future directions.....	14
References.....	16
Footnotes.....	18

List of tables

1. Coordinates of the six layouts. Each condition was associated with one array, created by the same seven round objects. Each layout represents one level of orthogonality (high, medium and low) and one level of symmetry (symmetric and non symmetric).
2. Contrast weights. In order to analyze the pattern of performance across headings, a contrast variable was computed by multiplying performance at every level of imagined heading with predetermined weights and adding all of these scores. These weights vary by condition to accommodate the different layouts and their headings.
3. Mean error. For each level of orthogonality (high, medium and low) and symmetry (symmetric and non symmetric), the error was averaged across heading.
4. Mean latencies. For each level of orthogonality (high, medium and low) and symmetry (symmetric and non symmetric), the latency was averaged across heading.
5. Chi-square values for the comparison between the preferred headings within each condition. The frequencies of the egocentric (315°) and allocentric (0° and 270°) preferred headings were compared, within each condition.
6. T-test values for the comparison between the pattern scores and zero. These comparisons indicate whether the patterns are significantly similar to the pattern of weights it is compared against.

List of figures

Figure 1. Traditional layout used in intrinsic studies. Array of objects used commonly in the literature (Mou & McNamara, 2002; Mou, Zhao & McNamara, 2007; Mou, Liu & McNamara, 2009; Greenauer & Waller, 2008).

Figure 2. Sawtooth pattern. The saw tooth pattern is characterized by a preferred direction at the 0° heading and facilitation at the 90° , 180° and 270° heading. The angle shows the imagined headings of the JRDs. The radial distance shows the JRDs' mean error.

Figure 3. Stimuli. The arrays used in each condition. The rows show each level of orthogonality (high, medium and low) and the columns show the two levels of symmetry.

Figure 4. Frequencies of preferred headings. The frequencies of preferred heading obtained in each condition. Only the participants who had an egocentric (315° heading) or an allocentric (0° and 270° heading) preferred heading are included.

Figure 5. Pattern of answers. The answers obtained across headings are presented across condition. The angle shows the heading and the radial distance depicts the difficulty.

Figure 6. Allocentric pattern analyses. The allocentric pattern analysis compares the pattern of answers obtained with the expected allocentric pattern. Along the Y-axis, positive values indicate that the participants' answers had a pattern of answer concordant with the expected allocentric pattern.

Figure 7. Egocentric pattern analyses. The egocentric pattern analysis compares the pattern of answers obtained with the expected egocentric pattern. Along the Y-axis, positive values indicate that the participants' answers had a pattern of answer concordant with the expected egocentric pattern.

Towards a Definition of Intrinsic Axes: The Effect of Orthogonality and Symmetry on the Preferred Direction of Spatial Memory

Spatial reference frames (or reference systems) provide the organization one uses to specify the locations of remembered objects in an environment (Klatzky, 1998). These systems can be based on, for example, the walls of a room, cardinal directions, or the experience of the observer. One of the major contemporary issues in spatial cognition involves understanding the bases and formation of reference frames in spatial memory. Identification of a reference frame in memory typically relies on the concept of a *preferred direction* – a direction from which memories of spatial relations are most easily retrieved (Shelton & McNamara, 1997; Presson, DeLange & Hazelrigg, 1987). However, diverging results throughout the literature have indicated different types of preferred directions.

Some studies have been consistent with an *egocentric approach to spatial memory*, which holds that the preferred direction of a memory of the environment is generally the same as the direction from which it was seen or learned (Greenauer & Waller, 2008; Shelton & McNamara 1997). For example, in one experiment, Greenauer and Waller (2008) asked participants to view a highly structured layout of eight objects (see Figure 1) and to remember the objects' locations. The participants were later tested on their knowledge through judgments of relative direction (JRD). JRDs ask the participant to imagine the layout from a specific point of view, or *imagined heading*, (e.g., "Imagine you are at the shoe, facing the clock") and then to point to a target object (e.g., "Point to the bottle"). Error and latency are then examined as a function of imagined heading, and headings with the least error (or latency) are inferred as being "preferred" in the participant's mental representation. Greenauer and Waller showed that participants remembered the layout best from their learning orientation and that performance decreased steadily as they responded to questions requiring increasingly discrepant imagined views. The preferred egocentric orientation was inferred as being directly represented in memory and steady decreases in performance were attributed to processes that transform this preferred direction into judgments involving increasingly discrepant views.

In contrast to these conclusions, other studies have demonstrated that preferred directions are not necessarily those that were directly experienced. Such results are consistent with an *allocentric approach to spatial memory* that posits that spatial memory is generally organized by

means of a non-egocentric reference system. Many studies have obtained results that support this hypothesis (Mou, Liu & McNamara, 2009; Mou & McNamara 2002; Mou, McNamara, Valiquette & Rump, 2004; Shelton & McNamara, 2001). For example, Mou and McNamara (2002) provided evidence for an allocentric representation by demonstrating that participants had a preferred direction based on the structure of the learned layout – not on their perspective during learning. The participants viewed the same highly-structured symmetric layout of objects used by Greenauer and Waller (2008, see Figure 1) from a point of view that was 45° away from the axis of symmetry (arbitrarily labeled 0°) and were instructed to learn the array according to the symmetric axis. Through JRDs, Mou & McNamara showed that the memory of the layout was facilitated at the instructed (symmetric) heading, relative to the learned heading, suggesting an allocentric representation of the layout.

Allocentric and egocentric reference frames present diverging accounts of an important and persistent issue in cognitive psychology: early or late processing. Do individuals process information more thoroughly upon encoding or upon retrieval from memory? The egocentric approach posits that individuals remember no more than their experience at learning. Upon retrieval, they then construct or generate the needed information from these remembered views. On the other hand, the allocentric approach holds that early processes operate during learning, perhaps creating a more flexible or abstract mental representation of the environment. When retrieving information about the environment, processing would be minimal and would allow more flexibility.

One way of reconciling the diverging findings between egocentric and allocentric approaches to spatial memory was suggested by Mou and McNamara (2002; see also Mou & McNamara, 2009;) as part of their “intrinsic theory of spatial memory.” According to this account, the preferred direction in spatial memory is determined by the array’s intrinsic axes (i.e., based on the characteristics of the layout of objects). In any given array, there are multiple potential intrinsic axes, and the viewer chooses one (or possibly a few) axis around which to organize spatial relationships. Mou and McNamara describe multiple cues that can influence the choice of an intrinsic axis (e.g., instructions) that may serve to explain how their participants were able to encode the array non-egocentrically. Moreover, according to this theory, findings that suggest a role for egocentric reference systems, such as those from Greenauer and Waller

(2008), may in fact illustrate the use of *egocentric cues* for selecting one of many possible intrinsic reference systems.

One current shortcoming of the intrinsic theory is its relative silence about the geometrical features of an array that give rise to an intrinsic reference frame. The theory states that “when people learn a spatial layout, they interpret the spatial structure in terms of an intrinsic reference system, one that is defined by the layout itself” (Mou & McNamara, 2002, p. 163). While this concept is clearly central to the theory, the external cues that can influence the choice of an intrinsic axis, aspects of the environment and instructions, have received more research attention than the geometric properties of the array (Mou & McNamara, 2002). The relative lack of research into the geometrical features of the layout seems surprising, given the use of the term ‘intrinsic’ to describe mentally represented spatial relations; certainly the surroundings and the instructions are not inherently (intrinsically) part of the learned layout. Consequently, it seems critical to the development of the intrinsic theory to explore how the structure of the layout influences the choice of a preferred axis in spatial memory.

The importance of geometric information in spatial memory has been investigated in the spatial cognition literature, although rarely with respect to frames of reference. For example, Cheng (1986) proposed that individuals rely on a geometric module in order to reorient. In his early work, he concentrated on the ability of rats to find food based on either geometrical information, e.g. the shape of a room, or on featural properties, e.g. shapes on the walls. Rats generally relied more heavily on the shape of the room than on featural properties in order to reorient. Following Fodor (1983), Cheng explained these findings by proposing a geometric module in which “one unit of the mind [...] encodes *only* the geometric properties in the arrangement of surface as surfaces” (Cheng, 1986, p. 172). More recently, Hermer and Spelke (1996) found support for this theory, showing that young children, when reorienting, relied exclusively on geometric information, i.e. on the shape of the environment. Although a wealth of subsequent evidence has cast doubt on the modular nature of Cheng’s proposal (see for example Cheng & Newcombe, 2005), researchers generally agree that environmental geometry is an important and frequently-used source of information for reorientation.

Some research has also begun to address how geometrical information might influence reference frame selection. For example, Mou, Zhao and McNamara (2007, experiment 3), examined the influence of array symmetry in the selection of an intrinsic axis. In their studies,

participants were asked to learn a symmetric layout from multiple angles and were subsequently tested on their knowledge of the array through JRDs. Participants in a second experiment learned a layout that was not symmetric. The results showed that for participants who learned a symmetric layout, the preferred axis in spatial memory was generally the symmetric axis. For those who learned a non symmetric layout, no preferred direction emerged, lending credence to the idea that the geometry of the layout itself influences the organization of spatial memory. It is important to note that participants in these experiments viewed the array from multiple directions, one of which was potentially symmetric. Consequently, for participants who learned the symmetric array, the symmetric axis was also egocentric, and it is therefore not entirely clear that the array was generally represented with a non-egocentric axis at all. In the proposed study, participants will view either a symmetric or non symmetric layout from a single point of view, enabling us to determine the degree to which symmetry enables one to represent an array non-egocentrically.

In addition to array symmetry, another characteristic of a layout that may influence the choice of a preferred axis is the array's orthogonality, defined here as the percentage of right angles among all possible angles in the array. Orthogonality was indirectly examined by Shelton and McNamara (2001) who studied the effects of an external environment on the choice of reference axis. In one experiment, the layout of objects was placed in a rectangular room. The participants viewed the layout from three points of view and their memory was then evaluated through JRDs. The results showed that the preferred direction in participants' memory of the array was aligned with the walls of the room (i.e., with its orthogonality). In another experiment, Shelton and McNamara asked participants to learn the array in a round room, from only one view point. The results indicated that the preferred axis was parallel to their viewpoint. One interpretation of these results is that the orthogonality of the room influenced the selection of the intrinsic axis. If so, it is possible that an observer's sensitivity to orthogonality can also apply to the array itself. Indeed, if right angles in the environment tend to induce people to choose the intrinsic axes parallel to them, then right angles in an array may have a similar effect.

Another interesting link can be made between array orthogonality and the "saw tooth" pattern of performance sometimes found across imagined headings, wherein performance is facilitated for imagined headings at 0, 90, 180, and 270 degree axes (relative to the 45, 135 and 225 degree axes – See Figure 1.) For example, in Mou and McNamara's studies (2002), when

the allocentric axis of 0° was preferred, the three associated axes were generally also preferred to the four egocentric axes, producing a saw tooth pattern (Figure 2). The saw tooth pattern suggests a role of orthogonality in spatial memory because it shows facilitation for the four headings that are aligned with the right angles in the array. The bond among these four headings may come from their parallelism with the orthogonality of the array.

Additional evidence from the perception literature suggests that orthogonality, when present, can affect the selection of a non-egocentric spatial reference frame. Goldmeier (1972) studied the ability of people to discriminate right angles according to their orientation. When participants viewed a right angle in a standing orientation (i.e., in a vertical-horizontal orientation, as an 'L'), they were more likely to discriminate it correctly from an 87 degrees or 93 degrees angle than when it was oriented to form an upside-down V. This suggests that right angles are more easily identified when they are in a standing position. Given this effect, it is possible that once an angle is identified as approximately a right angle, it is easier to remember it in its standing position. Thus, if people learn a highly orthogonal array from an off-angle, they may be more likely to remember it with a non-egocentric axis. In light of these findings, it can be hypothesized that a mental representation of an orthogonal array would be more likely to be remembered from an orientation where the right angles are standing. In the present study, participants learned arrays with either a high, medium, or low level of orthogonality. We anticipate that, as orthogonality diminishes, any non-egocentric preferred axis will have less of a perceptual basis and the layout will tend to be represented more egocentrically.

In the present study, we factorially manipulated orthogonality and symmetry to examine whether their combination also influences the selection of a preferred reference direction. While a high level of orthogonality may best be represented allocentrically and an array with no right angles may only be represented egocentrically, moderate levels of orthogonality might not be as salient. When symmetry is present in a moderately orthogonal array, it may help to orient the participant's memory of the array to the symmetric axis. Once the array is pictured allocentrically, the orthogonality can confirm the choice of this allocentric axis, because of the structure it provides. If, however, a moderately orthogonal array is not symmetric, the absence of symmetry will hinder the viewer from noting the orthogonality, leaving the participant with an egocentric memory of the array. Consequently, it can be hypothesized that a moderate level of

orthogonality will only result in a non-egocentric preferred axis if it is accompanied by symmetry.

Beyond these specific hypotheses, the larger goal of this research is to begin to ground the concept of intrinsic axes in physically measurable array properties. Such an effort will permit predictions about how a given layout of objects may be remembered, as well as providing greater definition and understanding of the intrinsic theory. Indeed, Mou and McNamara's intrinsic theory has heretofore been based primarily on one specific layout (Figure 1) that has been used across studies repeatedly. With only one layout, the variations in geometrical features of the array and their influence on the choice of an intrinsic axis cannot be explored. Indeed, the layout in Figure 1 is highly structured, symmetric, and orthogonal, and it is not clear which (if any) of these properties are most associated with people's tendency to remember it along non-egocentric axes.

In the present experiment, different groups of participants learned one of six arrays that vary systematically in their symmetry and orthogonality. Three levels of orthogonality (high, medium, low) were crossed with two levels of symmetry (see Figure 3). Different groups of participants were asked to learn one of these arrays and to answer a series of JRDs in order to evaluate the preferred direction in their memory of the space. We anticipated that non egocentric preferred axes would tend to be used for arrays that are high in orthogonality and/or symmetry and that symmetry is necessary in order to represent an array with moderate orthogonality non egocentrically.

Method

Participants

Ninety-seven undergraduate students (49 female), were recruited in return for credit in their Psychology class. Participants had a mean age of 19.00 years old. They were randomly assigned to one of the six conditions.

Materials

One of the six layouts depicted in Figure 3 was presented to each participant. The layouts were construed with the same set of seven common radially symmetric objects (flashlight, plate,

bottle, jar, ball, clock and cup). The coordinates of the layouts are presented in Table 1. To ensure that the layouts were not influenced by the geometry of the room, they were presented in a round room constructed of black fabric with a diameter of 3.00 meters. Each layout had eight imagined headings, all starting at the same arbitrary zero, depicted in Figure 3. Because of the differences among the layouts, the possible imagined headings across layouts could not all be equal. However, each layout was associated with eight imagined headings within the ranges of 0, 28-71, 77-90, 135, 180, 208-251, 257-270 and 315. Note that each layout has two objects that create an egocentric heading of 315 (and 135) as well as an intrinsic heading of 0 (and 180) and that participants viewed their array from the 315° heading.

For testing, JRDs were presented in a V8 head-mounted display from Virtual Research. The participants started and proceeded through each trial by pressing a hand-held mouse. They answered by turning their heads to indicate the direction of the target stimulus and then pressing a button on their mouse. The movement of the participant's facing direction was recorded with an inertial tracker (see Waller et al., 2002, for details of this method). Each participant received ninety-six JRDs, consisting of two blocks of forty-eight JRDs, presented in a random order within each block. Correct pointing directions (left/right and front/back), the frequency of imagined headings, the frequency of objects used as standing stimuli and the frequency of objects used as targets were counter-balanced within each block of JRDs.

Procedure

Participants were introduced to JRDs through practice trials with a small array of four objects. When the participant understood the task, they were told that they would be asked to learn a layout of eight objects. After being blindfolded, they were guided to an opening in the round room, where they faced the array from the 315° orientation. The participants then removed their blindfold for 30 seconds and studied the layout. They then put the blindfold back on and were asked to point to the objects and name them. These two steps were repeated at least three times and until the participant was able to name and point to all the objects correctly (as judged by the experimenter) three times in a row. Once they could point to each object in the layout, the participant was again blindfolded and guided to the testing room.

Testing began with six practice JRD trials and participants received error-corrective feedback on these trials from the experimenter. They then proceeded to the 80 test trials. Absolute pointing error and latency (defined below) were measured.

Design and data analysis

Two variables were manipulated between participants: orthogonality (3 levels) and symmetry (2 levels), creating six different layouts that were presented to the participants. Orthogonality was defined as the percentage of 90° angles among all possible triplets of objects in each array; however angles created with the objects along the same lines were only counted once. For example, in Figure 1, the angle created by the objects B, G and F and by D, G and F, was only counted once. By this definition, the three levels of orthogonality were high (13.3% right angles), medium (5.3% right angles) and low (no right angles). When right angles were present in an array, the large majority of them were oriented to the 0° heading¹. For symmetric arrays, the axis of symmetry was the 0° heading.

Latency on test items was defined as the time elapsed between the presentation of the orientation stimulus (e.g., “At the plate facing the cup”) and the beginning of the participant’s head rotation beyond 6 degrees. Pointing error was computed as the absolute value of the difference between the participant’s answer registered with mouse click and the correct answer. The principal analyses were performed on a variable labeled “Difficulty”, which represents the difficulty level of one particular trial compared to all other trials for each participant. Difficulty was computed for each trial by summing z-scores of the latency and error measures relative to each participant’s distribution of performance (see Waller et al, 2002).

The principal data analysis consisted of testing for predicted patterns (for more information about this technique, see Levin & Neumann, 1999). This technique allows researchers to analyze comprehensive *patterns* of data, and enabled us to differentiate between intrinsic and egocentric response profiles. This technique creates a contrast variable by multiplying performance at every level of imagined heading with predetermined weights and adding all of these scores. These weights vary between conditions to reflect the hypothesized role of each imagined heading. The contrast weights are presented in Table 2. A high contrast value obtained through this technique indicates a high match between the expected pattern and the results. Once obtained, a 2-way ANOVA (2 (symmetry) x 3 (orthogonality)) was performed

with egocentric and intrinsic contrasts as dependent variables. The ANOVA was then followed with appropriate contrasts and Bonferroni-corrected post hoc tests to evaluate the degree to which the results corresponded to the hypotheses.

Results

Of the 97 participants, one (in the non symmetric low orthogonality condition) was excluded based on excessive variability in JRD performance, with a mean error of 82°. Trials in which participants attempted to answer more than one time were eliminated. These trials were primarily due to hardware malfunction or to insufficient movement of the participant. A total of 115 trials were excluded (1.4%). The error and latencies are presented in Table 3 and Table 4. There was no evidence of a speed-accuracy trade-off within or across participants.

A preliminary set of analyses examined participants' preferred heading (defined as the heading with the lowest difficulty score) across conditions. These preferred headings were grouped in two categories: egocentric (315° heading) and allocentric (0° and 270° heading). Participants with other preferred heading ($n = 25$, or 26% of the total) were eliminated from these analyses. The frequencies of preferred headings for the other 74% of the participants are presented in Figure 4. In general, more participants displayed an egocentric preferred heading than an allocentric one. However, allocentric headings were generally preferred in the symmetric high orthogonality condition and the symmetric medium orthogonality condition. Chi-squares were performed for each of the six conditions to determine whether egocentric or allocentric preferred directions were over-represented (relative to equal representation). Only the symmetric medium orthogonality condition ($\chi^2(1, N = 16) = 5.33, p = .02$) and the symmetric low orthogonality condition ($\chi^2(1, N = 8) = 5.33, p < 0.01$) showed a significant difference between the two categories with a preference for the egocentric preferred heading. The chi-square results are presented in Table 5.

The primary set of analyses examined participants' *pattern* of responses across imagined headings (see Figure 5). In general, the results were more indicative of egocentrism than expected. These results did vary by condition, with the symmetric high orthogonality condition being particularly different from the other conditions, as it was the only one in which performance tended to exhibit an allocentric pattern.

These findings were first examined by computing a contrast variable for each participant that represented allocentric coding (see Figure 2) and then examining group differences on it via

ANOVA. The main effects of orthogonality ($F(2, 90) = 0.91, p = 0.52$) and symmetry ($F(1, 90) = 0.04, p = 0.86$) were not significant. However, the interaction between these two factors was significant ($F(2, 90) = 5.00, p = 0.009$). This interaction arose primarily because of the difference between the symmetric high orthogonality condition and the other conditions. This difference was significant as shown by the contrast comparing the symmetric high orthogonality condition to all other conditions, $F(1, 90) = 19.77, p < 0.001$. Moreover, the difference between the symmetric high orthogonality condition and the other five conditions explained 86% of the variance between conditions, $r_{\text{alerting}}^2 = 0.86$ (see Rosnow & Rosenthal, 2003). The remaining variance did not represent a significant proportion of the overall variance between the conditions, $F(4, 90) = 0.76, p = 0.55$.

As exhibited by these analyses and Figure 6, the symmetric high orthogonality array was the only array for which participants exhibited a positive mean allocentric contrast value, implying that it was the only condition in which participants generally exhibited the saw tooth pattern of responses predicted by the intrinsic theory. In this condition, the mean contrast value was marginally significantly greater than zero ($t(16) = 1.97, p = 0.07$). By contrast, the other two symmetric conditions, medium orthogonality ($t(15) = -3.58, p < 0.01$) and low orthogonality ($t(15) = -2.26, p = 0.04$) were significantly smaller than zero. For the non symmetric conditions, only the low orthogonality condition was significantly less than zero ($t(14) = -3.53, p < 0.01$), while the high orthogonality ($t(15) = -1.58, p = 0.13$) and medium orthogonality ($t(15) = -0.86, p = 0.40$) were negative (indicating a non-intrinsic pattern) but were not significantly different from zero.

The same analyses were then performed with the egocentric weights (Table 2). It is worth noting that the correlation between the egocentric and allocentric contrast weights is very low ($r(7) = .03$), indicating that these analyses are largely orthogonal with those in the previous paragraphs. This is also true for the values for the alternative weights used in the non symmetric medium orthogonality condition ($r = -0.06$) and the non symmetric low orthogonality condition ($r = 0.13$). The results are presented in Figure 7. Again, the main effects of orthogonality ($F(2, 90) = 0.50, p = 0.67$) and symmetry ($F(1, 90) = 2.06, p = 0.29$) were not significant; however, there was a significant interaction between these two factors ($F(2, 90) = 5.42, p = 0.006$). This interaction was primarily captured by the difference between the non symmetric high orthogonality condition and the other conditions, $F(1, 90) = 25.35, p < 0.001$. This contrast

explained 93% of the overall variability between conditions ($r_{\text{alerting}}^2=0.93$). The remaining unexplained variability did not represent a significant proportion of the overall variability between conditions, $F_{\text{failure}}(4, 90) = 0.50, p = 0.73$.

All the egocentric contrast scores were positive and significantly different from zero, suggesting that participants in all conditions tended to present an egocentric pattern of performance across imagined headings. All the t-tests scores are presented in Table 6.

Discussion

The intrinsic theory put forth by Mou & McNamara (2002) addressed the issue of which reference frames are used to organize spatial memory by proposing that people's preferred heading is aligned with intrinsic axes. Generally missing from this theory, however, is an account of how intrinsic axes might be defined, or could be determined before analyzing behavior. Instead, most research has defined the intrinsic axes as "salient" axes in the environment (Mou & McNamara, 2002) or has inferred intrinsic axes from behavioral data (Valiquette, McNamara & Smith, 2003). The present research begins to define the physical (geometric) characteristics that might underlie the use of intrinsic axes by concentrating on the saliency of orthogonality and symmetry. Participants were asked to memorize one of six arrays that represented a specific combination of orthogonality and symmetry and were subsequently measured on their memory of it. Patterns of performance across imagined headings were analyzed with the hypotheses that different physical array characteristics would be associated with different use of reference frames in spatial memory.

The results yielded three major conclusions. First, orthogonality and symmetry had an interactive effect on the reference frames used by the participants. Second, the array typically used in the literature, here used in the symmetric high orthogonality condition (see Figure 1), was the only array that was clearly associated with allocentric reference frames, suggesting that allocentric reference frames may not be as common as typically reported in the literature. Third, and related to the second finding, the majority of participants appeared to rely on an egocentric reference frame. These findings are discussed in turn.

Geometrical features

The main purpose of this study was to examine the potential effects of orthogonality and symmetry on the reference frames used by the participants. These geometrical features provide the beginning of an understanding of how intrinsic axes may be physically constituted. Such an understanding is critical in order to generate predictions from the intrinsic theory. We predicted that highly orthogonal arrays would be associated with allocentric reference frames whereas arrays with low orthogonality would encourage egocentric reference frames. With medium orthogonality, allocentric reference frames would be associated with only the symmetric condition. These hypotheses were not completely confirmed. Instead, the analyses revealed an unexpected interaction between orthogonality and symmetry wherein one condition differed significantly from the other conditions.

An unexpected way in which layout geometry influenced the choice of reference frames was seen in the non symmetric high orthogonality array (see Figure 3). Although an allocentric frame of reference was anticipated in this condition, the results were much more consistent with the array being represented by means of an egocentric frame of reference. After analyzing the results from this condition, we discovered that a symmetric axis was actually present in this condition, and that it was aligned with the egocentric facing direction. This was an unforeseen characteristic of the layout that should be avoided in subsequent research. However, this unintended symmetric axis does suggest that symmetry influences spatial memory as the pattern of answers shown by the participants in this condition was very close to the modeled egocentric pattern, even more so than any other condition. This indicates that symmetry may indeed be an array property that people leverage to organize spatial memory.

The modal array

The second major conclusion from this study involves the finding that the symmetric high orthogonality array was the only one that tended to be associated with a non-egocentric frame of reference. Because this condition presented the array commonly used in the literature, we refer to this array as the *modal array*.

In discussing the association between the modal array and the use of allocentric reference frames, it is instructive to consider how and why the modal array was first used. In their initial

work on the intrinsic theory, Mou and McNamara (2002) apparently designed the modal array to encourage allocentric reference frames by “making one intrinsic axis very salient” (Mou & McNamara, 2002, p. 164). Mou and McNamara claimed that “because of the extensive body of research demonstrating the important role of egocentric perspective in the formation of spatial memories, we were concerned that participants would have great difficulty representing a layout nonegocentrically” (p. 164). Thus, Mou and McNamara designed a highly structured layout and incorporated many cues, including symmetry and high orthogonality that highlighted the intrinsic axis. The present results confirm the findings of Mou and McNamara (and many subsequent studies) that this particular structure is favorable for remembering with respect to allocentric frames of reference. Consistent, too, with Mou and McNamara’s interpretation, we suggest that the modal array provides such strong nonegocentric cues that viewers are inclined to represent it by means of an allocentric reference frame.

Egocentricity

Perhaps the clearest finding from this study, however, was that for all but the modal array, participants’ performance was most consistent with an egocentric preferred direction. The analyses indeed suggested that the participants mainly remembered the layout by referencing the objects’ locations to their own orientation at learning. This is consistent with previous findings in the literature (e.g., Greenauer & Waller, 2008) which demonstrate the possible use of egocentric frames of reference when learning arrays of objects, and suggests that critical spatial processing occurs at retrieval, instead of encoding.

Since Mou and McNamara’s (2002) initial work on the intrinsic theory, much of the subsequent research aimed at refining this theory has also used the modal array. All four publications (Greenauer & Waller, 2008; Mou, Liu & McNamara, 2009; Mou, Zhao & McNamara, 2007; Valiquette, McNamara & Labrecque, 2007) about the intrinsic theory used the modal array. Across these papers, 10 conditions were involved and 6 of these 10 conditions used the modal layout. This relative over-use of the modal array in the literature may be problematic, especially if the scope of the theory is to apply to the variety of spatial layouts that people routinely encounter. Indeed, allocentric reference frames could have been observed because of this array, and not because viewers actually tend to use allocentric frames of reference.

Of course the finding that most arrays in the present study were coded with an egocentric preferred axis does not necessarily invalidate or cast doubt on the intrinsic theory. An intrinsic theorist could interpret the present data by stating that participants always used an intrinsic axis and that, in the present experiment, it happened to be aligned with their egocentric facing direction at learning. Yet such an explanation is ultimately a post-hoc description of these results – not an explanation that would enable predictions of future behavior. Our attempts to ground the concept of intrinsic axes in physical array properties may begin to provide a parsimonious explanation of spatial memory, and one that may need to incorporate the notion of egocentric reference frames.

In comparison, other interpretations propose that preferred directions aligned with the egocentric viewing directions indicate an egocentric reference frame. This would imply that in the absence of a salient intrinsic axis not aligned with the egocentric viewing direction, individuals default to the egocentric viewing direction and rely on an egocentric reference frame. While still consistent with the intrinsic theory, this interpretation offers a more parsimonious interpretation of the results obtained in the present study.

Future directions

One limitation of the present study was that only a single array was used in each condition. It is possible that the particular choices of array introduced additional geometrical features that could have interacted with the orthogonality and symmetry variables. For example, the symmetric axis parallel to the egocentric viewing point in the non symmetric high orthogonality condition was an unexpected geometrical attribute that had an effect on the results. It is possible that other such features could have also had an influence on the results. Subsequent research should include other arrays to account for these superfluous factors.

Finally, this study attempted to define intrinsic axes, but only by way of two factors. It would be pertinent to pursue these ideas by exploring other geometrical features of the environment that might influence the choice of an intrinsic axis. For example, orthogonality in the present study was defined as the percentage of right angles, and most of the right angles in these arrays had the same orientation. A valuable follow-up study could examine the effect of right angles when their orientation varies within an array. Once thoroughly defined, a definition

of intrinsic axis based on physical array characteristics will give a better understanding of reference frames and thus spatial memory.

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Footnote

1. The use of Mou and McNamara's (2002) "standard" layout required that a small percentage of the right angles in it were not aligned with the axis of symmetry (e.g., angle ADF in Figure 1).

Table 1

Coordinates of the Objects in each of the Layouts depicted in Figure 1

Orthogonality	Symmetric		Non symmetric	
	X	Y	X	Y
High	0	0	0	0
	0	3	0	2
	3	0	2	0
	3	3	2	2
	3	6	2	6
	6	0	6	2
	6	3	6	6
Medium	0	1	0	4
	0	5	1	0
	2	0	1	5
	2	4	3	0
	2	6	3	5
	4	1	4	1
	4	5	4	2
Low	0	0	0	1
	2	5	1	2
	3	0	1	4
	3	7	4	5
	3	8	5	0
	4	5	5	3
	6	1	6	1

Table 2

Contrast Weights

Symmetric and High Orthogonality							
0	45	90	135	180	225	270	315
-1.625	0.375	-0.625	1.375	-0.625	1.375	-0.625	0.375
-0.750	0.250	1.250	0.250	1.250	0.250	-0.750	-1.750
Symmetric and Medium Orthogonality							
0	45	90	135	180	225	270	315
-1.625	0.375	-0.625	1.375	-0.625	1.375	-0.625	0.375
-0.750	0.250	1.250	0.250	1.250	0.250	-0.750	-1.750
Symmetric and Low Orthogonality							
0	45	90	135	180	225	270	315
-1.625	0.375	-0.625	1.375	-0.625	1.375	-0.625	0.375
-0.750	0.250	1.250	0.250	1.250	0.250	-0.750	-1.750
Non Symmetric and High Orthogonality							
0	45	90	135	180	225	270	315
-1.625	0.375	-0.625	1.375	-0.625	1.375	-0.625	0.375
-0.750	0.250	1.250	0.250	1.250	0.250	-0.750	-1.750
Non Symmetric and Medium Orthogonality							
0	71.55	90	135	180	251.55	270	315
-1.404	0.006	-0.404	1.596	-0.404	0.416	-0.404	0.596
-0.750	0.840	1.250	0.250	1.250	-0.340	-0.750	-1.750
Non Symmetric and Low Orthogonality							
0	26.57	78.69	135	180	206.57	258.69	315
-0.483	-0.302	1.266	-0.232	0.483	0.698	0.020	0.517
-0.656	-0.066	1.092	0.344	1.344	0.754	-1.154	-1.656

Note. The first row of each condition presents the weights of the allocentric predicted pattern whereas the second row lists the weights of the egocentric predicted pattern. Note that the contrast weights accounted for the unequal spacing of the headings.

Table 3

Mean Error (in degrees) and Standard Deviations for Each Condition

Heading	High	Orthogonality Medium	Low
Symmetric			
0	25.36 (12.32)	38.24 (17.29)	49.51 (8.90)
45	40.55 (18.40)	31.78 (13.57)	30.20 (15.59)
90	33.11 (13.20)	34.61 (15.12)	32.45 (14.02)
135	34.65 (21.80)	29.10 (13.54)	37.98 (10.45)
180	34.44 (21.57)	42.49 (11.94)	33.63 (18.66)
225	36.26 (17.43)	29.91 (15.03)	32.87 (11.54)
270	32.05 (15.85)	28.20 (16.15)	32.19 (12.99)
315	26.02 (12.24)	30.04 (11.71)	20.65 (8.52)
Non symmetric			
0	26.30 (13.01)	46.73 (13.97)	34.00 (13.14)
45/71.55/26.57	37.48 (18.09)	32.67 (12.28)	50.81 (13.91)
90/78.69	43.30 (24.77)	44.98 (17.62)	35.00 (13.12)
135	41.14 (24.96)	48.40 (23.20)	41.52 (14.30)
180	44.53 (21.66)	53.04 (22.25)	44.69 (23.93)
225/251.55/206.57	26.09 (16.02)	32.91 (11.23)	43.71 (18.57)
270/258.69	28.51 (12.85)	24.35 (8.60)	27.07 (8.61)
315	23.47 (6.80)	29.98 (12.22)	23.25 (9.76)

Note. Participants learned from the 315° heading and the axis of symmetry (when present) was the 0° heading.

Table 4

Mean Latencies (in degrees) and Standard Deviations for Each Condition

	High	Orthogonality Medium	Low
Symmetric			
0	8.73 (1.84)	10.30 (3.87)	8.95 (2.98)
45	10.29 (2.84)	11.52 (3.29)	9.27 (2.60)
90	9.68 (2.85)	11.44 (3.49)	10.20 (3.10)
135	9.50 (2.27)	9.73 (3.50)	8.31 (2.22)
180	9.71 (2.21)	12.61 (5.04)	8.69 (2.63)
225	9.91 (2.67)	11.52 (5.46)	9.52 (2.51)
270	10.33 (3.72)	9.74 (3.30)	8.43 (2.40)
315	8.81 (2.03)	8.77 (2.79)	7.22 (1.86)
Non symmetric			
0	8.87 (3.35)	11.96 (7.46)	11.74 (2.91)
45/71.55/26.57	10.82 (4.22)	10.61 (3.72)	9.38 (2.98)
90/78.69	10.22 (2.29)	10.44 (4.24)	9.82 (3.21)
135	8.71 (2.32)	10.99 (5.42)	9.07 (1.74)
180	11.88 (3.06)	10.25 (4.74)	10.31 (3.76)
225/251.55/206.57	9.77 (3.31)	10.13 (3.37)	10.21 (3.22)
270/258.69	8.48 (1.70)	9.00 (2.45)	8.52 (2.23)
315	6.93 (2.23)	8.99 (2.66)	8.18 (2.77)

Note. Participants learned from the 315° heading and the axis of symmetry (when present) was the 0° heading.

Table 5

Chi-square values for the comparison between the preferred headings within each condition

Orthogonality	Symmetric			Non Symmetric		
	Chi-square	df	Sig	Chi-square	df	Sig
High	0.69	1	0.41	0.60	1	0.44
Medium	5.33	1	0.02	0.33	1	0.56
Low	8.00	1	0.01	0.69	1	0.41

Note. Indicates relative over-representation of egocentric preferred heading among participants in the condition.

Table 6

T-test scores contrasting the pattern of answers' contrast values against zero

Orthogonality	Pattern	Symmetric			Non symmetric		
		t	df	sig	t	df	sig
High	Allocentric	2.08	16	0.05	-1.60	15	0.13
	Egocentric	4.87	16	0.00	10.40	15	0.00
Medium	Allocentric	-3.66	15	0.00	-0.99	15	0.34
	Egocentric	4.61	15	0.00	3.74	15	0.00
Low	Allocentric	-2.80	15	0.01	-3.48	14	0.00
	Egocentric	3.94	15	0.00	4.81	14	0.00

Note. Positive t scores indicate evidence for the tested pattern.

Figure 1. Array of objects used commonly in the literature (Mou & McNamara, 2002; Mou, Zhao & McNamara, 2007; Mou, Liu & McNamara, 2009; Greenauer & Waller, 2008).

Figure 2. The sawtooth pattern. The saw tooth pattern is characterized by a preferred direction at the 0° heading and facilitation at the 90°, 180° and 270° heading. The angle shows the imagined headings of the JRDs. The radial distance shows the JRDs' mean error.

Figure 3. Stimuli. The arrays used in each condition. The rows show each levels of orthogonality (high, medium and low) and the columns show the two levels of symmetry.

Figure 4. Frequencies of preferred headings. The frequencies of preferred heading obtained in each condition. Only the participants who had an egocentric (315° heading) or an allocentric (0° and 270° heading) are included.

Figure 5. Mean difficulty (defined in the text) obtained across headings are presented across condition. The angle shows the heading and the radial distance depicts the difficulty.

Figure 6. Allocentric pattern analysis. The allocentric pattern analysis compares the pattern of answers obtained with the expected allocentric pattern. Along the Y-axis, positive values indicate that the participants' answers had a pattern of answer concordant with the expected allocentric pattern.

Figure 7. Egocentric pattern analysis. The egocentric pattern analysis compares the pattern of answers obtained with the expected egocentric pattern. Along the Y-axis, positive values indicate that the participants' answers had a pattern of answer concordant with the expected egocentric pattern.