2018

Semantic and Structural Influences on Spatial Knowledge Acquisition

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SEMANTIC AND STRUCTURAL INFLUENCES ON SPATIAL KNOWLEDGE ACQUISITION

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

By

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2018

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MAY 8, 2018

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Abstract

May, Robert B., M.S., Human Factors and Industrial/Organizational Psychology Program, Department of Psychology, Wright State University, 2018. Semantic and Structural Influences on Spatial Knowledge Acquisition

Spatial memory for the layout of large-scale environments, configural spatial memory, has typically been construed as being very structured, using something like a metric coordinate system and using environmental objects to define that coordinate system. Inside of buildings, rectangular rooms have walls at right angles that have been considered to fulfill this role. However, the influence of non-spatial factors and considerations of relatively unstructured environments have not received much attention. Semantic organization was found to improve configural spatial memory for landmark objects in rooms with walls and it was independent of the structural relations among landmark objects (Colle & Reid, 2000). The mechanism behind this semantic effect is not well-understood. The present study also used semantic organization (grouping landmarks) and manipulated structural information in a different way, by comparing walled rooms with equivalent non-walled quadrants. It also randomized landmark object placement, providing minimal structural cues in non-walled conditions. Participants experienced a single tour of four rooms/quadrants using a random path to visit each landmark object. Participant performance was measured by having them both create sketchmaps of the environment and make angular judgments between objects using a direction circle. As expected, absolute angular error was smaller for walled environments than those without walls. Results from the sketchmaps showed that semantically grouped landmarks improved performance when walls were present, but the effect was not statistically significant without walls. In contrast, results from directional pointing queries, the other memory retrieval measure, showed that semantically grouped landmarks did improve performance without walls, but the effect was not significant when walls were present. These data suggest that people can acquire configural spatial knowledge quickly in relatively unstructured environments and that verbal effects can improve spatial memory in both structured and relatively unstructured conditions. Potential explanations are discussed.

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ACKNOWLEDGEMENTS

I would be remiss not to start by thanking my advisor, Dr. Herbert Colle. Your guidance and support made all this possible. I sincerely appreciate it.

Next, I want to thank my committee members Dr. Scott Watamaniuk and Dr. Assaf Harrel. Your contributions were insightful and your perspectives much needed.

I also wish to thank my host of research assistants, without whom this would have taken much longer and been considerably less enjoyable. Thanks go to Arielle Stephenson, Emily Chriswell, Jacqueline Brito, Lucia Jimenez, Abigail Shoop, Alannah Reiley, and Kaitlin Fine.

Last, I would like to thank my friends, family, and especially my fiancé for keeping me relatively sane during this process.

I. INTRODUCTION

The ability to navigate our environment important. Although navigating depends on the acquisition, storage and retrieval of spatial knowledge, the cognitive mechanisms underlying spatial knowledge are not well-understood, despite having been the subject of considerable research and theory. The current research seeks to contribute to this body of research by evaluating an assumption common to many theories: that configural spatial memory representations of an environment are best described as a mental Cartesian coordinate system. This assumption will be addressed in greater detail shortly.

The proposed research deals with spatial knowledge acquired from and important for large-scale navigation. Research from stationary viewing or from single glances of a local environment appears to be less relevant. For information acquired via navigation, Siegel and White (1975) described a commonly used taxonomy of three types of representations of spatial knowledge stored in human memory, which they called: landmark, route, and configural spatial memory representations.

Siegel and White (1975) defined landmark knowledge as objects or clusters of objects and environmental features that “...specify a specific geographic location.” Note that there is an enormous range of possible forms that landmarks can take though they are nearly always visual in nature. What people use as landmarks in particular environments is an empirical question which has been investigated (Caduff & Timpf, 2008; Miller &

Carlson, 2010; Sorrows & Hirtle, 1999). Properties of landmarks appear to include combinations of being unique, distinctive, large, immoveable, and meaningful.

Route knowledge uses landmarks to describe a path through an environment. It describes a procedure for getting from one place, the origin, to another, a destination. They are often what we communicate verbally when giving turn-by-turn directions to someone, with each step simply directing them to the next landmark. Although landmark information is a component of route knowledge, route knowledge also includes spatial actions such as turn left at a landmark. Distances and angular relations are not specified or they are only crudely specified categorically. Although Siegel and White (1975) called them "sensorimotor routines" more recently this spatial knowledge has been treated more as declarative or verbal episodic knowledge, which would only become nondeclarative procedural knowledge with extended practice on a route (Dethlefs, Wu, Kazerani, Winter, 2011).

The current research is focused on Siegel and White's third type of memory representation, configural spatial memory representations, sometimes called survey knowledge. It also uses landmark knowledge, but its spatial representation consists of multiple spatial interrelationships of metric or quasi-metric relations such as angles and distances among landmarks. Configural spatial knowledge is thought to underlie human understanding of environmental layouts and provide flexibility when navigating in unfamiliar environments, especially when a route is unknown, blocked, or erroneously navigated.

Metric Coordinate Systems

Framework Theories. The predominant approach taken to describing human configural spatial knowledge of landmark layout assumes that configural spatial memory representations exist as a human metric space with an analytic geometry coordinate system (e.g., Meilinger, 2008; Meilinger, Riecke, & Bülthoff, 2010; Wagner, 2006). These theories may refer to our representations of configural knowledge as cognitive maps (Tolman, 1948) or as survey knowledge as in maps from surveying. As Colle (2018) has argued, Tolman's conception of cognitive maps was similar to current conceptions of working memory or of Baars' (1988, 1997, 2002) conception of global workspace theory, or his analogy of theater of consciousness as a decision planning screen. Unlike Tolman, framework theories assume that cognitive maps are two-dimensional plan view maps similar to physical cartographic maps. Framework theories focus on finding framework stimuli that define the mental metric coordinate system. Thus, landmark information such as walls are used as framework cues which can be used to determine the orientation of the axes of the mental metric coordinate system (e.g., Levinson, 1996).

Multiple Local Framework Theories. However, theories that assume that configural spatial knowledge is map-like face a major problem. Because the map-like representations are treated as a metric space with an analytic coordinate system, configural spatial representations form a mental coordinate system and they should satisfy the axioms of a metric space. Unfortunately for such theories, behavioral research has demonstrated that our spatial representations repeatedly fail to do so (Gollege, 1997; McNamara, 1986; Wagner, 2006; Zhang, Mou, McNamara, & Wang, 2014). For instance, distance judgments from memory between pairs of points have been shown to be consistently non-reversible, meaning that a stated distance from point A to point B did not correspond to responses to later queries about the distance from point B to point A. This is a violation of the symmetry assumption for coordinate spaces, which states that such reversals must be symmetrical. Similarly, judgments of angles between sets of familiar landmarks often exceed the prescribed totals for those shapes (e.g. more than 180 degrees between a trio of points) and usually by a considerable margin (Moar & Bower, 1983).

Attempts have been made to account for these violations. The most prevalent of such attempts include the proposal of multiple local coordinate systems or of a hierarchical nesting of such systems that become less detailed as you move up the hierarchy (Greenauer & Waller, 2015; McNamara, 2008; Meilinger, 2008; Zhang et al., 2014). An example of the former titled the "Network of reference frames theory" proposed that people have a coordinate system reference for each particular environment and that these are networked by loose connections that denote the approximate direction from one reference frame to another (Meilinger, 2008). Meilinger (2008) proposed that by breaking up a single reference frame cognitive map into many smaller ones, any violations of a metric space can be explained by assuming that the two components are on different reference frames and thus do not share firm geometric relationships. However, this is not a satisfactory explanation because a method for identifying the boundaries of each reference frame has not been proposed, leading to circular logic whereby axiom violations are justified by assuming different reference frames and the identification of separate reference frames depends only on the axiom violations. In addition, for each proposed local metric space the origin of the axes, as well as their orientation and scale would need to be specified in order to make predictions from an explicit theory.

A Spatial Memory Theory without a Coordinate System

The OBSERVE Theory. Recently, a non-framework theory, the "Object-Based Spatial-Episodic Representations for Visual Environments (OBSERVE) theory" of configural spatial memory was proposed by Colle (2018). Overall, it assumes that configural spatial memory is similar to verbal/linguistic memory, which has been the primary focus of much memory research. Accordingly, both memory systems use retrieval as well as encoding processes. Retrieval tasks include both cued and free recall (technically reproduction) and configural recognition. Also, they both distinguish episodic from conceptual (also called semantic) memory systems. However, configural spatial memory differs in one important way from verbal/linguistic memory; configural spatial memory representations include angular and distance information in addition to verbal/linguistic information.

Three specific assumptions of the OBSERVE theory are relevant to the proposed research. First, it assumes that coordinate system frameworks are not necessary as the bases of spatial memory. Configural knowledge consists of angles and distances, but there is no need to put them into metric coordinate systems. People may learn the angle between two buildings and know little else about the surrounding area. Structures or prominent landmarks may provide more general concurrent relationships among several different objects, but this subset of landmarks is not necessary for spatial learning to occur. Second, spatial memory is not defined by points in space, which are required for

Cartesian coordinates. Rather, it is defined by object-to-object relationships, or relationships among sets of objects. Landmarks typically are solid three-dimensional objects or semi-permanent environmental features. In addition to a location, they often have a distinctive orientation. In a built-up environment, one aspect of an orientation is to have a distinctive front, back, or side. Thus, descriptions of X, Y coordinates as locations for objects are not sufficient to describe human configural spatial knowledge. Distinctive object orientations also may be included as a component of memory representations. Finally, a comparable processing assumption is a component of the OBSERVE theory. According to this assumption, configural spatial memory processes should be the same as or similar to the memory processes used for verbal/linguistic memory. These similar processes of encoding, retrieval and thinking generate or interact with memory representations in both configural spatial and verbal/linguistic memory systems. The two memory systems are distinguished primarily by the addition of spatial angle and distance information to configural spatial memory. Memory representations of configural spatial memory consist of angular and distance codes as well as the verbal/linguistic codes, which have been studied historically in non-spatial learning tasks (Colle, 2018).

Relational/Distinctiveness Processing. One learning and memory theory mentioned explicitly as a potential component of OBSERVE theory is the multifactor relational/distinctiveness-processing framework (Hunt & McDaniel, 1993). Its processing assumptions have described important aspects of verbal/linguistic memory acquisition. According to the multifactor relational/distinctiveness processing framework, both relational and distinctiveness processing are critical for learning verbal/linguistic information. Relational processing forms connections between items or concepts that are perceived as similar and links them within a superordinate unit. For example, for lists of words from obvious superordinate categories, the semantic relationships among words also provide categorical information. If a person retrieves a category, then they can execute retrieval searches within that category, which might yield many words/word concepts. On the other hand, distinctiveness processing uniquely identifies items that are within these superordinate units and is effective at reducing intrusions or false recall, distinguishing words in the category that were actually presented during the learning phase from other words in the category that were not presented.

The operation of Hunt and McDaniel's concepts can be seen in the results of Tulving and Pearlstone's (1966) seminal article, which demonstrated the need for a concept of retrieval. Tulving and Pearlstone made a distinction between availability of information and its accessibility. Information is available if a representation of it is stored in the memory system, but information can be available but not accessible, meaning that it is stored in memory but cannot be retrieved. Tulving and Pearlstone had participants learn lists of categorized words from several different common categories with multiple words from each category. There were two initial groups, one was given the category names as cues during recall and the other group was not. The cued group recalled more words than the uncued group did. However, participants were given a second round of recall testing (without additional learning) during which both groups were given the category cues. The important result was that the participants that received the cues only during the second round of testing (the uncued/cued group) showed a significant improvement in the number of words recalled on the second test, similar to the performance of the category-cued group. Participants that had cues on both trials (the cued/cued group) and the uncued/uncued group showed no improvement. These results clearly demonstrated the importance of retrieval. However, they also are consistent with the concepts of relational (categorical organization) and distinctiveness with categories. The categories were the relational component and the improvement of the non-cued/cued group was produced by the number of categories recalled; they recalled the same number of words per recalled category as the cued/cued group. The importance of distinctiveness is the limitation that was found in the number of words that could be recalled from a category. They found that when the number of words per category was large, it became difficult to distinguish among all the words in the subgroup, thus limiting how many words in a category were recalled (see also Mandler, 1967).

Consistent with the comparable processing assumption, Hoelscher and Colle, (2014) showed that for configural spatial learning physical structural elements (e.g., walls) acted analogously as category cues do for verbal/linguistic learning. The analogy is that room walls and doorways act as spatially superordinate cues. They are more global landmarks to which all of the local landmark objects in the room can be spatially related. While category concepts refer to semantic relationships, structural concepts refer to spatial relationships, angles or distances. In both cases, the cues depend on well-known conceptual memory knowledge, semantic or spatial structural. Colle, Hoelscher, and Knipper (2018) duplicated the paradigm of Tulving and Pearlstone (1966) but tested spatial knowledge, and obtained similar results; participants who received cues on the first spatial memory test performed better. Cues in their spatial experiment were in the form of the environment’s structure (i.e. the walls), instead of semantic categories, which provided potential retrieval cues for objects in the rooms that participants visited. Again, there were two rounds of testing and three groups: uncued/cued, uncued/ uncued, and cued/cued. On cued retrieval trials, participants were given the structural wall information; they only had to put the local landmark object information on the map. On uncued retrieval trials, participants had to put the same local landmark object information on a blank page and the participants were not allowed to draw in the walls. Participants in the uncued/cued group showed great improvement in performance (reduction in angular error) between the two rounds of testing and their second round was not statistically different than the cued/cued group's, which showed no such improvement. The uncued/uncued group's performance stayed constant, and was not different from the first round of the uncued/cued group's performance. From these results it seems that the structure of rooms can be viewed as analogous to Tulving and Pearlstone's semantic categories, forming an organization of groups for spatial information about landmark objects. In another experiment, Knipper and Colle (2014) coded electronic movies of participants sketching maps of environments they had visited virtually and they found that structural elements such as walls were always drawn before individual landmark objects, suggesting that the structures acted as superordinate cues. Finally, Douglas's dissertation research (2017) showed that structural information could be measured directly and appeared to be processed differently than individual local landmarks. Both Douglas (2017) and Knipper and Colle (2014) defined physical structural information as walls, doorways, and hallways. The current thesis used this same definition, though hallways were not present.

Structural components of an environment, such as walls, do not appear to be the only means of facilitating spatial organization. Semantic relationships between objects in an environment can also affect spatial information stored about them. For instance, in an experiment by Colle and Reid (2000) participants navigated within and between rooms in a virtual environment composed of three rooms connected by a hallway with three objects in each room. Measures of subject performance were taken using a map-drawing task and a directional pointing judgment task. As in other experiments, structural features were important. Angular error for a pair of landmark objects that were in the same room (within-room pairs) was lower than when the two objects were in different rooms (between-room pairs). However, they also found that participants had reduced angular error when landmark objects in a given room were all from the same semantic category (e.g. Appliances) than when the objects were all from different categories. The semantic grouping factor was independent of the location of the landmark object pairs (within-room or between-room); the interaction was not statistically significant. Semantic relations led to improved spatial knowledge independent of just spatial structural relations, when landmark objects were grouped semantically by room. Interpreted through Hunt and McDaniel's (1993) relational/distinctiveness theory of learning, these results may indicate that the semantic similarity of landmark objects helps to produce more effective spatial relational processing among these objects. Rizzardo's (2016) dissertation results also showed evidence for semantic grouping and for distinctiveness processing by demonstrating that when participants received elaborated information for a category of landmarks (those relevant to errand destinations) there was an ideal range for the number of landmarks to provide during GPS-like navigation. Providing enough errand-relevant landmarks to enable ad-hoc group formation improved performance. However, providing too many errand-relevant landmarks (more than four) made it difficult to discriminate between the group members in memory, and so performance fell.

The Current Experiment

This experiment further evaluates the usefulness of semantic organization as a medium for conveying configural spatial information. Colle and Reid (2000) showed that semantic organization could work in conjunction with spatial structure. Participants learned spatial knowledge of landmark objects by exploring a virtual environment with landmark objects in typical rooms with walls, etc. (spatial structures). The current research examines if semantic organization can be useful when participants learn about an environment where there is little or no spatial structure, especially the type of spatial structure that is considered to be important for spatial frameworks (e.g., walls).

To test this, I developed a virtual environment in which two factors were manipulated: (a) spatial structure, the presence of useful frameworks assumed to be necessary for proposed coordinate systems, and (b) semantic organization of objects. A third factor quadrant pair type also was added, the relative locations of pairs of landmark objects in the environment. Let us consider these factors one at a time.

Spatial Structure: Spatial structure was manipulated as a two-level factor: present and absent. In this case structure took the form of room walls. One level added structure to the category condition by adding walls that divided a larger space into four quadrants with doorways to walk between them and walls to enclose the environment, forming four rooms (see Figure 1). The other level had no walls, but was otherwise identical (see Figure 2). This virtual environment extended well beyond the line of sight and contained a constrained uniformly distributed set of local landmark objects such that there was no obvious intrinsic structure defined by object locations or by the edges or boundaries in the environment. In addition, the fronts of these objects were randomly oriented. The objects were distributed randomly with a uniform distribution and equally among four equal-sized square quadrants that comprised the total area of the virtual environment. In short, the walls provided the only clear axes along which a coordinate system could be created in the virtual environment that participants experienced, and thus it should not be possible to form such a grid when they are absent.

Semantic Organization: There were two levels of semantic organization: grouped and distributed. Local landmark objects were grouped semantically when each quadrant/room only contained objects from a single semantic category, so that each room was associated with a unique category. Local landmark objects were distributed semantically when each quadrant/room contained one landmark object from each of the four semantic categories, so that there was no systematic relationship between semantic categories and quadrants/rooms.

Quadrant Pair Type: A third, non-manipulated factor was also included for the purpose of data reduction. Unlike the previous two factors, this factor was a repeated measures factor. It refers to the relative positions of the environment quadrants containing the landmark objects used to calculate measures of subject performance. How this is done will be covered in detail in the methods section. In short, these relative quadrant positions were formed by dividing the performance data into three types of comparisons on pairs of landmark objects: within, between lateral, and between diagonal. The within quadrant pair type was used to describe pairs of objects that both were located in the same quadrant of the environment. The between lateral quadrant pair type was used to describe pairs of objects that were located in laterally adjacent quadrants. Lastly, the between diagonal quadrant pair type was used to describe object pairs that were located in two quadrants that were not adjacent, but were instead diagonally opposite one another. As mentioned previously, Colle and Reid (2000) demonstrated that angular error for pairs of landmark objects that were in the same room (within-room pairs) was lower than when one was in the same room and one in another room (between-room pairs). This reduction in error for within-room pairs was called "the room effect" (Colle & Reid, 2000). This factor was included in order evaluate how the room effect might be influenced by our other factors. These three factors were crossed to form a 2 x 2 x 3 mixed factorial design.

If walls as spatial frameworks are necessary for defining a mental metric coordinate system framework, and such coordinate systems are required for the formation of spatial knowledge then there are two expected results. Firstly, there should be no effect of semantic grouping, as semantic categorization has no bearing on the formation of coordinate grids and would thus be irrelevant. Second, there should be much better performance when walls are present than without walls. The acquisition of spatial knowledge should not be possible without walls and doorways to define the axes of the mental coordinate system, as long as no other axes such as ordered columns and rows of landmark objects are pressent.

If instead, the predictions of the OBSERVE theory are correct then there should be a much different pattern of results. In this case, the presence of walls during learning would enhance spatial knowledge acquisition (reduce angular error), as they would serve as superordinate cues with which object to object relationships can be organized. The grouped semantic organization would also yield performance superior to that of the distributed organization, as the semantic categories would provide another framework for organizing the relationships between the landmark objects. This should be particularly evident when walls are absent, as semantic categorization would then be the only available framework with which to organize the angular relationships between landmarks. Lastly, the acquisition of spatial knowledge should still be possible without walls and doorways and without ordered columns and rows of landmark objects to define the axes of the mental coordinate system.

II. Methods

Participants

A total of 96 subjects were tested in the experiment; 24 were randomly assigned to each of the four between-subjects conditions. Participants were required to have normal or corrected to normal visual acuity and normal color vision, normal hearing, and speak English as their first language. Lastly, participants were excluded if they participated in any of our previous spatial memory experiments.

Equipment

The testing area consisted of six booths separated by dividers. Each booth contained an Apple iMac computer (Model 7.1) configured by Boot Camp to use a Windows 7 operating system. Each monitor's screen measured 42.3 x 27.1 cm and had a screen resolution of 1680 x 1050 pixels, with a 60-Hz refresh rate, and was controlled by an ATI mobility Radeon HD 2400 XT video card with a 32-bit color palette. Each participant was given a pair of headphones to hear narration during their experience in the virtual environment and to hear the audio of the instructional videos in the map pointer program.

Virtual Environments

The virtual environment and the objects to be learned were created using the Google SketchUp 3D design program. The functional environment was a square with virtual dimensions of 96 feet x 96 feet (29.26 m x 29.26 m). This single environment was used for all conditions, with the manipulations of structure and semantic organization reflected by changing the visibility of walls and the categorical grouping of local landmark object sets.

Walled Rooms. In the walled rooms environment, the overall square was divided by walls into four smaller square quadrants, each with virtual dimensions of 48 feet by 48 feet (14.63 m x 14.63 m), which I refer to as rooms. The walls were 10 feet (3.05m) high and 4 inches (10.16 cm) thick. The walls separating these rooms from each other had openings that were 19 feet (5.79m) wide and centered on the wall, so that the walls to either side of each opening extended 14.5 feet (4.42m) from each side of the room. Wide doorways facilitate using more variable and natural movement paths between rooms. In this way, participants in the no-walls condition, whose navigation used the same path, were less likely to perceive any potential divisions between rooms due to the navigation path. This floor plan is shown in Figure 1. The doorway openings between rooms are bridged at the top by an arch that serves as the top of the "doorframe". The walls were textured with stone blocks and the floor was a matte single color. Both of these can be seen in Figure 1. There was no floor to the environment. The walls and objects rested on the default placement plane of the environment. The blue color that can be seen in the Figure 1 and 2 was the same featureless background as the virtual sky.

No walls. In the no walls environment, there was only a large area without any walls or boundary markings. This was the same environment that was used in the walled condition, except that the walls were invisible. This environment can be seen in Figure 2.

Landmark Object Placement and Orientation.

Landmark Object Placement. All objects were large 3D solid objects with a noticeable front side. In order to place the objects, each of the four 48 x 48 ft. quadrants was further divided into a 4 x 4 grid creating 16 sub-quadrants of 12x12 ft. (3.66m). Each of the 16 sub-quadrants could have no more than one landmark object in it. Four locations for object placement were randomly assigned for each individual quadrant using a Latin square procedure with the 4 x 4 sub-quadrant grid of rows and columns in each quadrant. First, a row was randomly selected. Next, a column in that row was randomly selected, identifying a unique (row, column) cell. This procedure was followed for two more rows, with the restriction that each column could be used no more than once. The column of the fourth remaining row was at that point completely determined. After the four sub quadrants were chosen, each one was divided into a 3 x 3 grid with each cell of this grid being 4 ft. x 4 ft. (1.22m) and one of these nine cells was chosen randomly with equal probability. The center of one of the landmark objects was then aligned with the center of that cell. A diagram of the chosen locations can be seen in Appendix E.

Landmark Object Orientation. After the four placement locations per quadrant were determined, the orientations of the fronts of objects at each location were determined. Every landmark object had a rectangular envelope and an identifiable front side. Thus, as with many environmental solid three-dimensional objects, they had an orientation, which can be defined with respect to other objects in the environment or to an observer. For measurement purposes, this orientation was defined explicitly by noting the relative direction of the front of a landmark object, which in this experiment could be in one of four orthogonal directions. These directions were named arbitrarily A, B, C, and D for experimenters' identification and as rectangular objects these front sides formed 90-degree angles with respect to adjacent sides. Of course, participants had no information about these local landmark object orientations other than the visual cues they experienced; the experimenters' directional names for the fronts of landmark objects were not known to them. These orientations were chosen randomly with the restrictions that no more than two objects in a quadrant could be oriented in the same direction and that all orientation directions must be used equally often across all four of the quadrants in the environment (each orientation used exactly four times). The same 16 location/front orientation pairs were used in all four experimental conditions. Each one of these location/front orientation pairs had one of the landmark objects randomly assigned to it. This random assignment was restricted by the grouped versus distributed factor.

Landmark Object Categories. The 16 landmark objects that were placed in the four quadrants comprised four members from each of four common categories of large indoor objects: appliances, arcade games, drink vending machines, and furniture. Pictures of the objects in each category along with the category and object names are shown in Appendix B.

In addition to the previously mentioned criteria, the objects had to be considered indoor objects and belong to a well-known category of at least four members. I conducted a pilot study to collect norming data on 80 potential objects so that the objects and chosen categories would be readily identifiable by our participants. I collected data from 60 participants and selected the 16 objects that were most consistently named and identified as belonging to the same consistently identified four categories.

Navigation Paths

Participants saw a first-person view of navigation through the virtual environment from a view height of 5ft., 2in (1.57m). Appendix C shows examples of point of view perspective images. This was chosen instead of allowing participants to control the navigation themselves, in order to keep the amount of learning time constant for all participants and standardize object views. Participants also heard a script which described the object being searched for. They were navigated to each object in the environment, not necessarily directly, and ended up facing the front of each landmark object from about an arm's length away.

The navigation path was created by randomly generating a path between the 16 objects. To prevent potentially alerting participants in the no-walls condition to the invisible room divisions, the following constraints were placed on the possible path sequence: 1) No more than two objects in the same quadrant were visited in sequence and 2) No more than three of the quadrants could be visited in a single clockwise or counter-clockwise circuit. Transitions between quadrants were balanced such that the participant left and entered each quadrant (room) the same number of times. The navigation path did not follow straight-line routes between objects, instead using curvilinear paths that afforded sweeping views of each room allowing the participant to see each local landmark object from many vantages and distances. The path began with the eye point facing the first object in the visitation sequence, from roughly 4 meters away. Appendix E shows the listing of the order in which the locations were visited, along with the landmark objects at each location for the grouped and distributed conditions.

Measurement Programs:

Sketch Maps. A custom program was created using the Java software development kit 5.0 to create and play instructional audio and videos, provide sketching tools, display the participants' sketches, and to save the participants' sketchmaps and relevant measures and experimental information. The program interface was displayed over the entire screen of the monitor and divided into two major sections, a drawing space and a toolbar. The usable drawing space was 40.7 x 26.5 cm (1573 x 1021 pixels) with a side toolbar measuring 2.6 x 26.5 cm (100 x 1021 pixels).

Directional Pointing Program. Another custom program was created to record directional pointing judgments. Participants made object-based directional judgments (OBJ) based on queries from the program. To make OBJ judgments participants were told to imagine that they are squarely facing the front of a named landmark (facing object) object from an arm's length away, and that they should now point to a second named object (target object). An example of a presented query is "You are standing in front of the Pepsi machine. Point to the dog house." The OBJ angle is formed from the perpendicular line from the observers' position to the front of the facing object and a line from the object's position to the target object. A response to such a query is recorded when the participant marks a point on a direction circle that is divided into five-degree intervals with these divisions being denoted by the alternating blue and gray colors in the intervals. Appendix A shows a screen shot of the direction circle.

Together, the facing and target objects comprise a pair. There are three pair types which I refer to as within, between-quadrant lateral (lateral), and between-quadrant diagonal (diagonal). The first refers to a pair of objects that are both in the same quadrant of the environment. The second type, refers to a pair in which the quadrant that contains the facing object shares a border with the quadrant containing the target. The last type refers to a pair in which the quadrants containing the facing and target objects do not share a border, and are thus diagonally across the environment from one another.

The procedure for selecting the object pairs to be used for the pointing queries was as follows:

1. It was decided that there would be 32 total queries, made up of two blocks of 16. Each of these blocks was further divided by the three pair types: 8 within pairs, 4 between (lateral) pairs, and 4 between (diagonal) pairs.
2. These queries were then balanced evenly across the four quadrants, so that each would have two within pairs, one between (lateral), and one between (diagonal)
3. Each object pair was determined by first randomly selecting the facing object from the given quadrant using a random number generator. The target object was then randomly selected from the appropriate quadrant(s).
4. The random selection of objects had two major constraints
    a. Each object was chosen once as a facing object and once as a target.
    b. No reversals were allowed (i.e. if A1/A3 was an existing pair, then A3/A1 was not acceptable).

Experimental Conditions

The experimental design was a 2 x 2 x 3 mixed factorial design with one between-subjects factor of structural organization (walls, no walls), the second between-subjects factor of semantic organization (grouped, distributed), and the third repeated-measures factor being the quadrant query type (within-quadrant query, between lateral quadrant query, between diagonal quadrant query). In the walls conditions, walls were visible along the quadrant lines as shown previously in Figure 3. In the no walls condition, there were no interior or exterior walls visible.

The grouped versus the distributed conditions determined the semantic organization of landmark object placement within the quadrants. In the grouped condition, each quadrant/room contained only local landmark objects from a single semantic category, so each of the four categories was used in only one randomly determined room. In the distributed condition, each of the four categories of objects was equally distributed among the four rooms. Thus, each room contained one object from each category.

Quadrant queries are within-quadrant when both landmark objects in the query are in the same quadrant. Quadrant queries are between-quadrant when both landmark objects in the query are in different quadrants. Between-quadrant queries were further divided into lateral and diagonal queries. Between lateral pairs were between two objects from different quadrants that share a common border. The between diagonal pairs were those objects that belonged to different quadrants which did not share a common border.

Procedure

Participants watched one of the four videos, one for each of the four experimental between-subject conditions in the 2 x 2 x 3 factorial design: no walls/grouped, no walls/distributed, walls/grouped and walls/distributed. Each video was roughly 7 minutes in length, with minor variation between them due to editing. An equal number of participants were randomly assigned to each of the four experimental conditions.

During each experimental session, participants experienced the following sequence of events: spatial learning from the virtual environment, free recall of landmark object names, directional pointing and map sketching in counterbalanced order across participants within each experimental condition.

Before watching a virtual environment video of navigating through a warehouse, participants heard a description of the scenario. The same scenario was described to all participants, in which they were asked to inventory a set of objects that had just been moved into a large warehouse. They were told that the objects had been moved by several different trucks at different times and that the inventory list was put together by someone else who is responsible for the objects but was not involved in the move. This person did not know where these objects were placed in the warehouse, but participants were told to go down the list in order so that they would not miss any of the objects. Therefore, they were to search among the objects to check them off according to the sequence on the list. The exact script that was read to the participants during this segment appears in Appendix D.

Following this description, the participants were told to pay close attention to what they see in the video. The experimenter then began the video. During the video, they heard a script (via headphones) describing what the next landmark object on the list was, and indicating when they arrived at the landmark object being sought. This script was written as though it was the subject's internal monologue, and the remarks were designed to help them identify objects and to comment on major object features. For example, if the next item in the sequence was the writing desk they would hear: "Now, a writing desk". Then, upon reaching the desk they would hear "Wow, this is an old one. Looks like it could be an antique". When finished watching the video, they received instructions on how to free recall the names of the objects they saw in the video. They had 4.5 minutes to complete the free recall task after the recall tutorial was concluded. Following this, participants began a tutorial for either creating a sketchmap or using the directional pointing program. All participants performed both of these tasks; the order of which was counterbalanced across participants within each of the four groups.

Sketch Map Task: Participants used the mouse in conjunction with the custom sketch map program to place the video landmark objects in their relative positions on an otherwise blank map. Participants first familiarized themselves with the necessary program commands by creating a practice map of the testing room. These practice maps were then reviewed by the experimenter to see that the subjects understood how to use the program tools and that the map was reasonably accurate. Upon successfully completing the practice map, participants began the map of the virtual environment using the same tools as in the practice. Each landmark object was represented by a square box and they were required to place all sixteen of the boxes, affix an object name to each, and mark their fronts before the map was considered complete. The box's X and Y coordinates were used to calculate Object Based Judgment (OBJ) angles for pairs of landmark objects. Participants did not put walls or doorways on the map. For a detailed explanation of the usage of this program, see appendix A.

Directional Pointing Task: Participants used an electronic direction circle to make a series of Object Based Judgments (OBJs). The tutorial for this task explained how to interpret the OBJ prompts and how to use the direction circle to respond by selecting among the five degree increments around its' circumference. The participants then responded to a set of practice prompts based on objects in the testing room, requiring the experimenter's approval of their selection for each query before they could proceed to the next prompt. If a response was not reasonably accurate then the experimenter worked with the participant to show them why it was not correct and how to more accurately imagine the given scenario. If a participant still did not appear to understand the task after the practice queries had been completed, then their data was not used and was replaced by testing another participant. There were a total of 4 such replacements. Landmark objects were used equally often as facing objects and a target objects in queries. The specific usage of the pointing circle is shown in Appendix A.

Configural Spatial Memory Measurement

Angular Measures: Both the directional pointing judgments and sketchmaps were used to independently calculate participant performance in the form of absolute angular error. For the directional pointing judgments, the program output the angles chosen by the participants on the direction circle. These angles were then compared against the true angles obtained by using the exact coordinates of the objects in the virtual environment. Similarly, the sketch map program reported the coordinates of the objects placed by the subject from which were used to calculate response angles to compare against the true angles. In both cases the result was the absolute value of the angular error for each pair of facing and target objects.

The absolute value of the angular difference for the angle between a pair of objects on the sketch maps, R_{ij}, and the comparable angle between the pairs in the simulated environment, T_{ij}, was calculated and used as the absolute angular error, E_{ij} (Batschelet, 1981). Equation 1 shows how the shortest error distance around the circle was calculated. The absolute angular error difference, E_{ij}, had a minimum of 0° (completely accurate), a maximum of 180°, and a chance level of 90° (see Appendix Q for how this chance level was determined).

$$E_{ij} = \text{Minimum}\left[\, |R_{ij} - T_{ij}|\,,\ 360 - |R_{ij} - T_{ij}| \,\right] \qquad \text{Eq. (1)}$$

Once each of these absolute angular errors had been computed, they were combined into three average error scores: within quadrant error, between lateral quadrant error, and between diagonal quadrant error. The first was the mean error from an object to other objects with which it shared a quadrant. The between lateral error was the mean error between pairs of objects that were from different quadrants that shared a common border. Lastly, between diagonal error was the mean error between object pairs that came from different quadrants that did not share a border. These three scores were used as measures of configural spatial knowledge.

It should be noted that I used two methods of averaging the above three angular error measures for the sketch map data. The first of these methods found the mean of all possible object pair combinations: 120 unique object pairs comprising 24 within quadrant pairs, 64 between lateral pairs, and 32 between diagonal pairs, and another 120 pairs which were reversals of the unique pairs (e.g. A1 to B3, became B3 to A1). This was the primary data set I used from the sketchmap task and I refer to this data set as the all-map data. The second method found the mean for only the objects pair combinations that were chosen for the pointing task queries: 16 within quadrant pairs, 8 between lateral, and 8 between diagonal, for a total of 32 pairs. This was done to ensure that I could compare differences between the map and pointing tasks with identical sets of object pairs. I refer to this smaller data set as the map data pointing-equivalent pairs. These two sets along with the data from the pointing task, are the three sets analyzed in the results section below.

Data Analysis

A set of 11 orthogonal contrasts was used to evaluate our predictions, with an alpha level of .05. The contrast table for these can be seen below in Table 1 and in Appendix F. The between-subjects conditions were split into contrast-a: grouped versus distributed for walls only and contrast-b: grouped versus distributed for no walls only. There was also contrast-c: an overall wall versus no wall contrast. The 2 degrees of freedom for repeated-measures were split into contrast-d: within-room/quadrant versus the mean of lateral and diagonal (between-room/quadrant) and contrast-e: lateral versus diagonal. The other six contrasts were the interactions of the between-subjects and repeated-measures contrasts. As mentioned previously, these analyses were performed on three data sets: the all-map data, the pointing data, and the sketch map pointing-equivalent pairs data.

We also intended to do these same analyses on a subset of the data determined by which objects the subjects were able to free recall. This would have allowed us to see how the ability to free recall objects influenced performance by organizing the data in

Table 1. Orthogonal Contrasts

		Walls						No Walls					
		Distributed			Grouped			Distributed			Grouped		
Contrast		Within	Lateral	Diagonal	Within	Lateral	Diagonal	Within	Lateral	Diagonal	Within	Lateral	Diagonal
DvG: Walls	a	1	1	1	-1	-1	-1	0	0	0	0	0	0
DvG: No Walls	b	0	0	0	0	0	0	1	1	1	-1	-1	-1
Walls v NoWalls	c	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1
Within v Btwn	d	1	-0.5	-0.5	1	-0.5	-0.5	1	-0.5	-0.5	1	-0.5	-0.5
Lateral v Diag	e	0	1	-1	0	1	-1	0	1	-1	0	1	-1
	a x d	1	-0.5	-0.5	-1	0.5	0.5	0	0	0	0	0	0
	b x d	0	0	0	0	0	0	1	-0.5	-0.5	-1	0.5	0.5
	c x d	-1	0.5	0.5	-1	0.5	0.5	1	-0.5	-0.5	1	-0.5	-0.5
	a x e	0	1	-1	0	-1	1	0	0	0	0	0	0
	b x e	0	0	0	0	0	0	0	1	-1	0	-1	1
	c x e	0	-1	1	0	-1	1	0	1	-1	0	1	-1

two groups of object pairs: one group in which both objects in each pair were recalled (the RR group), and a second group in which neither object was recalled (the NRNR group). However, the mean recall among our participants was very high (*M*=13.56 out of 16 objects, *SD* =1.73), indicating that the NRNR category was almost completely empty, which would cause distortions in the analyses due to floor effects. Therefore, this analysis was not performed. The RR data were analyzed and found to have similar results to the initial analyses that were conducted without concern for recall status.

In addition to the measures of angular error above, free-recall data were analyzed. First, the number of objects that were free recalled was analyzed, as this has been taken as a measure of Siegel and White's (1975) category of landmark knowledge. Second, two methods of scoring clustering, category and quadrant, were analyzed to see if walls or semantic grouping had any effect on clustering, Clustering was measured by counting the number of category runs in the free recall output order for each participant. A run is one or more object names from the same category bounded before and after by another category or the ends of the list. Any number of items from the same category that were recalled in succession was counted as one run. Thus, the fewer runs a participant had, the more clustered their recall data was. Two clustering scores were computed for each participant: one based upon the semantic category an object name belonged and another based upon the quadrant the named object had been located. Each had a minimum possible score of 4 runs (perfect clustering) and a maximum of 16 runs (no clustering), assuming that all 16 object names were recalled. Thus, the effects of semantic grouping and/or walls on semantic and spatial clustering could determined.

III. Results and Discussion

Planned Orthogonal Contrasts

Sketch Map Data-All Pairs: As the top panel of Figure 4 shows, grouping objects by their semantic category in the quadrants produced a marked reduction in angular error (M = 52.0º) compared to when they were semantic distributed across the quadrants (M = 65.5º), when walls were present. This contrast-a was statistically significant, $F(1, 92) = 4.77$, $MSE = 1373.5$, $p = .032$. This result is consistent with the results of Colle and Reid (2000) who only used a walls condition. The difference between semantically grouped and distributed objects (contrast-b), as shown in the bottom panel of Figure 4, was less pronounced when walls were absent (M = 63.9º vs. 72.5º, respectively) and was not statistically significant, $F(1, 92) = 1.94$, $MSE = 1373.5$, $p = .167$.

As the top panel of Figure 4 shows when walls were present, both the distributed and grouped conditions produced comparable angular error for all three quadrant pair types (within, lateral, and diagonal). The interactions of semantic grouping with within versus between-quadrants/rooms (contrast a x d) and the interaction of semantic grouping with lateral versus diagonal pair types (contrast a x e) were not statistically significant, $F(1, 92) = 0.29$, $MSE = 60.43$, $p = .593$ and $F(1, 92) = 0.03$, $MSE = 21.28$, $p = .873$, respectively. These results were consistent with the results of Colle and Reid (2000), who found no interaction between semantic grouping and within versus between room pairs.

The bottom panel of Figure 4 shows that when walls were absent the three quadrant pair types were not quite as uniform as they are in the top panel when wall were present. The distributed curve nominally decreased more than the semantically grouped one, but the differences between them was not statistically significant, as shown by the interaction of semantic grouping with within versus between-quadrants (contrast b x d, $F(1, 92) = 2.36$, $MSE = 60.43$, $p = .128$). As before, the interaction of semantic grouping with lateral versus diagonal pair types (contrast b x e) also was not statistically significant, $F(1, 92) = 2.01$, $MSE = 21.28$, $p = .159$. Thus, semantic grouping did not interact significantly with quadrant pair type for both no walls and walls environments.

As predicted, angular error between pairs of objects was also significantly reduced by the presence of walls ($M = 58.8^{o}$), compared to when there were no walls in the environment ($M = 68.2^{o}$), $F(1, 92) = 4.64$, $MSE = 1373.5$, $p = .034$ (contrast-c). However, the effect of walls interacted with within versus between quadrant pairs (contrast c x d), $F(1, 92) = 5.75$, $MSE = 60.43$, $p = .019$. With walls, mean angular error was 58.70º for within-quadrant/room and was 58.85 º for between-quadrant/room. Without walls, the comparable angular error was 71.21º for within-quadrant and 66.69º for between-quadrant. Walls did not interact with lateral versus diagonal quadrants (contrast c x e), $F(1, 92) = 2.37$, $MSE = 21.28$, $p = .127$. Comparing both panels of Figure 4 shows that angular error with walls present in the top panel was relatively flat for all three quadrant pair types. This result is consistent with previous research, which has found that within-room and between-room pairs produced comparable angular error when people navigated between walled rooms directly without going into hallways (Colle & Reid, 2000). In contrast, without walls present in the environment, the bottom panel of Figure 4 shows that angular error was highest for within-quadrant pairs and decreased for between room pairs with the major decrease occurring between the within-quadrant and the lateral-quadrant pairs. This decrease is a new phenomenon. Previous quadrant/room effects found an increase in angular error from within to between room pairs when people navigated from room to room via hallways and little or no difference when they navigated directly from room to room without traversing hallways. The overall effect of within versus between quadrants (contrast-d) was also statistically significant, $F(1, 92) = 5.06$, $MSE = 60.43$ $p = .027$, which was most likely driven by the contrast-c x d interaction. The overall lateral versus diagonal quadrants (contrast-e) was not statistically significant, $F(1, 92) = 0.63$, $MSE = 21.28$, $p = .428$. The contrast table output for all of these analyses can be seen in Appendix G.

A chi-square test of goodness of fit was also conducted to see if the sketchmap data in the no-walls conditions were significantly better than chance (lower than 90º). For all 48 participants in the no-walls condition (both semantically grouped and distributed) 44 of them (91.7%) had performance better than chance, showing that the no-walls group performed better than chance, $X^2 = (1, N = 48) = 33.3$, $p < .001$.

Directional Pointing Data: This data set produced a somewhat different pattern of results than the map data. The top panel of Figure 5 shows that when walls were present, angular error appears to be lower when objects were organized semantically ($M = 63.11º$) than when they were not ($M = 75.53º$), as it was for the sketch map data. However, contrast-a though close, was not statistically significant, $F(1, 92) = 3.36$, $MSE = 1369.32$, $p = .069$. When walls were absent, the angular error for objects organized semantically (M = 63.9º) was similar to objects that were distributed (M = 72.51º), as it was for sketch map data. This contrast (contrast-b) was not statistically significant, $F(1,92) = 0.21$, $MSE = 1369.32$, p = .648.

Consistent with the sketch map results, when walls were present, semantic distribution did not interact with quadrant pair type, either for the between versus within quadrant pair contrast (contrast a x d) or for the lateral versus diagonal quadrant pair (contrast a x e), $F(1, 92) = 1.05$, $MSE = 170.97$, $p = .308$ and $F(1, 92) = 0.01$, $MSE = 218.84$, $p = .938$, respectively. The difference in angular error between semantically grouped and distributed sets of objects was similar for all three types of quadrant pairs as can be seen in the top panel of Figure 5.

However, unlike the sketch map data, contrast b x d shown in the bottom panel of Figure 5 was significant, $F(1, 92) = 8.57$, $MSE = 170.97$, $p = .004$. When walls were not present, grouping objects semantically produced a greater reduction in angular error for pairs of objects grouped in the same quadrant ($M = 71.18°$ grouped vs. 83.03° distributed) than it did for between quadrant object pairs ($M = 75.59°$ grouped vs. 73.90° distributed). As the bottom panel of Figure 5 shows, the major angular error difference producing this interaction was between the within-quadrant versus the lateral quadrant. This pattern is supported by contrast b x e, the interaction between semantic distribution by lateral vs diagonal quadrant pairs, which was not statistically significant, $F(1, 92) = 2.52$, $MSE = 218.84$, $p = .116$.

In contrast to the findings of the map data, contrast c found no significant mean difference in error between those conditions with walls ($M = 68.76°$) and those without ($M = 75.53°$), $F(1, 92) = 2.41$, $MSE = 1369.32$, $p = .124$. Also unlike the map data, no significant c x d interaction emerged between walls and the within versus between quadrant pair type, $F(1, 92) = 0.68$, $MSE = 170.97$, $p = .411$. However, the finding that the c x e interaction between walls and the between lateral versus diagonal pair types was also not significant, was consistent with the map data findings, $F(1, 92) = 1.96$, $MSE = 218.84$, $p = .165$. These findings are evident in Figure 5, which shows that the presence or absence of walls did not much change the relative uniformity error of the three quadrant pair types.

Lastly, it should be noted that neither contrast d (within versus between quadrant pairs) nor contrast e (between lateral versus diagonal quadrant pairs) were significant. $F(1, 92) = 0.38$, $MSE = 170.97$, $p = .539$ and $F(1, 92) = 2.12$, $MSE = 218.84$, $p = .149$, respectively. The latter finding is consistent with the map data findings, but the former is not. As mentioned previously, the significance of the map data contrast d was largely driven by its interaction with the effect of walls. The fact that no difference was found in the pointing data between the within and between quadrant pair types (contrast d) is likely because walls were not as effective here at reducing error as they were with the map data. See Appendix H for the full contrast analysis output pertaining to this section.

A chi-square test of goodness of fit was also conducted to see if the pointing task data in the no walls conditions were significantly better than chance (lower than 90º). For all 48 participants in the no walls condition (semantically grouped and distributed) 34 of them (70.8%) had performance better than chance and 14 were worse than chance, showing that the no walls group as a whole performed better than chance, $X^2(1, N = 48) = 8.33$, $p = .004$. A follow-up test was conducted using only the data from the within-quadrant pairs subset of the no-walls, semantically distributed condition data; the mean closest to the chance line. For this data point 18 of the 24 participants had performance better than chance (75.0%) and 6 participants had performance less than chance. This chi square also was shown to be significantly different from chance performance, $X^2(1, N =$

24) = 6.00, p = .014

Sketch Map Data-Pointing-equivalent Pairs: In this analysis, only the sketch map pairs that matched those used for directional point queries to participants were analyzed. The top panel of Figure 6 illustrates the effect of contrast a, showing a similar pattern to that found in both the pointing and map data when walls were present. Angular error was less when objects were grouped semantically (M = 53.42º) than when they were not (M = 65.60º). However, as with the pointing data this difference was not quite significant, $F(1, 92) = 3.38$, MSE = 1577.53, p = .069. The no-walls contrast b seen in the bottom panel was also consistent with both the map and pointing data, with the difference between the two types of object grouping also not being significant $F(1, 92) = 1.18$, MSE = 1577.53, p = .281.

However, the findings from this data set align more closely with the sketch map results, than with the pointing data results for the interactions of semantic grouping and quadrant pair type. Consistent with the map data, when walls were present semantic distribution did not interact with quadrant pair type, either for the between versus within quadrant pair contrast (contrast a x d) or for the lateral versus diagonal quadrant pair (contrast a x e), $F(1, 92) = 0.62$, MSE = 148.03, p = .433 and $F(1, 92) = 2.56$, MSE = 221.27, p = .113, respectively.

The difference in mean angular error between semantically grouped and distributed sets of objects was similar for all three types of quadrant pairs as can be seen in the top panel of Figure 6. However, as the bottom panel of Figure 6 shows, this general

pattern also held true for those conditions in which walls were absent as well, unlike the directional pointing data. Semantic grouping did not interact significantly with quadrant pair type for the within versus between contrast (contrast b x d), $F(1, 92) = 2.08$, $MSE = 148.03$, $p = .153$. Nor was its interaction with the lateral versus diagonal contrast (contrast b x e), consistent with both the directional pointing and all pairs of the sketch map data, $F(1, 92) = 0.26$, $MSE = 221.27$, $p = .612$.

A final similarity with the pointing data was found in contrast (c), with no significant difference in error found between the walled environments ($M = 59.25^{\circ}$) and those with no walls ($M = 68.45^{\circ}$), $F(1, 92) = 3.02$, $MSE = 1577.53$, $p = .085$. However, a significant interaction emerged: that of (contrast c) walls and (contrast d) within versus between (mean of lateral and diagonal) quadrant pairs. Fig. 6 shows that the presence of walls reduced error to a greater extent for within quadrant pairs ($M = 58.48^{\circ}$ walls vs. 70.84° no walls) than it did for the mean of lateral and diagonal quadrant pairs ($M = 60.02^{\circ}$ walls vs. 66.05° no walls), $F(1, 92) = 4.33$, $MSE = 148.02$, $p = .040$. The other interaction of walls (contrast c) and between lateral versus diagonal quadrant pair type (contrast e) was not significant, which is consistent with both of the results of the other two data sets, $F(1, 92) = 2.28$, $MSE = 221.27$, $p = .135$.

The pointing equivalent map data set also yielded a different pattern of quadrant pair type effects than either of the other two data sets. The first of these was the significant contrast between lateral and diagonal quadrant pairs (contrast e); an effect not shown by either the map or pointing data. Figure 6 shows that error was significantly higher for diagonal quadrant pairs ($M = 66.44^{\circ}$) than it was for lateral quadrant pairs ($M = 59.63^{\circ}$), $F(1, 92) = 10.06$, $MSE = 221.27$, $p = .002$. However, the non-significant difference between within quadrant and between quadrant pair types, was consistent with the findings of the pointing data, $F(1, 92) = 1.14$, $MSE = 148{,}03$, p = .288. See Appendix I for the full contrast output for this section.

Factorial Anovas

In addition to the above contrasts, we conducted an overall 2 x 2 x 3 mixed factorial anova with between-subjects factors of wall (walls, walls) and distribution (grouped, distributed category members) with a repeated-measure factor of quadrant pair type (within, lateral, diagonal quadrants). This anova was used to compare these results with those of Colle and Reid (2000) more directly, as they did not employ orthogonal contrasts. Where appropriate, Greenhouse-Geisser corrections are shown with the F ratios as p_{gg} and the error correction given as ε_{gg}, but the original degrees of freedom and MSEs are shown. As with the contrasts, this ANOVA was performed on all three data sets.

Sketch Map Data-All Pairs: In their (2000) paper, Colle and Reid found a large main effect of semantic organization and a significant effect of room pair types (quadrants with walls are rooms). Similarly, the current data also found an effect of semantic grouping, with absolute angular error significantly reduced when semantic members of the categories were grouped in the same quadrant ($M = 57.98^{o}$) compared to when they were distributed among quadrants ($M = 69.20^{o}$), $F(1, 92) = 6.40$, $MSE = 1373.5$, $p = .013$. The comparable comparison in the current data to their room pair type would be the quadrant pair type, which was significant, $F(2, 184) = 3.91$, $MSE = 40.86$, $\varepsilon_{gg} = 0.766$, $p_{gg} = .032$. As explained in the Introduction, an effect of quadrant pair type was not expected in the present experiment because navigation did not use hallways to go from room to room as they did in Colle and Reid (2000). Finally, the interaction of semantic organization with quadrant pair type was not statistically significant, $F(2, 184)$

= 1.79, MSE = 40.86, ε_{gg} = 0.766, p_{gg} = .178, which is also consistent with Colle and Reid (2000).

The present experiment added the factor of wall structure. Angular error was reduced when walls were present (M = 58.79º) compared to when they were not (M = 68.20º), $F(1, 92) = 4.64$, MSE = 1373.5, p = .034. This factor is identical to contrast-c in the contrast analyses. Importantly, a significant interaction did emerge between wall structure and quadrant/room pair type, $F(2, 184) = 4.87$, MSE = 40.86, ε_{gg} = 0.766, p_{gg} = .015. The orthogonal contrasts indicated that this was because there was no difference when walls were present (contrast a x d), but angular error decreased from within-quadrant to between-quadrant without walls present (contrast b x d).

Lastly, the interaction of wall structure and semantic grouping was not statistically significant, $F(1, 92) = 0.31$, MSE = 1373.5, p = .577, nor was there a three-way interaction of these two and quadrant pair type, $F(2, 184) = 0.69$, MSE = 40.86, ε_{gg} = 0.766, p_{gg} = .465. The full ANOVA output for this analysis can be seen in Appendix J

Directional Pointing Data: As we saw with the contrasts, the pointing data produced a different pattern of results from that of the map data. Unlike the map data, the difference in error between those objects which were grouped semantically (M = 68.61º) and those which were not (M = 75.68º) was not significant, F(1, 92) = 2.63, MSE = 1369, p = .108. No main effect of quadrant pair type emerged either, although this is consistent with the map data, $F(2, 184) = 1.36$, MSE = 194.9, ε_{gg} = 0.97, p_{gg} = .260. Angular error was however significantly affected by the interaction of quadrant pair type and semantic organization, $F(2, 184) = 4.07$, MSE = 194.9, ε_{gg} = 0.97, p_{gg} = .020. Figure 7 shows that grouping objects semantically yields a major reduction in error for within quadrant pairs

(M = 66.24º grouped vs. 79.40º distributed), but that this improvement over non-semantic grouping is much decreased for between lateral quadrant pairs (M = 67.10º grouped vs. 73.41º distributed) and is smaller still for between diagonal quadrant pairs (M = 74.24º grouped vs. 72.50º distributed), although the contrast analyses indicated that there were no significant differences between lateral and diagonal pair types.

Consistent with the pointing data contrast c comparison of walls versus no walls, no significant effect for walls emerged from this ANOVA, $F(1, 92) = 2.41$, $MSE = 1369$, $p = .124$. As with the map data, there was no interaction between walls and semantic grouping $F(1, 92) = 0.95$, $MSE = 1369$, $p = .333$. Similarly, there was no three-way interaction of these two and quadrant pair type, $F(2, 184) = 1.57$, $MSE = 194.9$, $\varepsilon_{gg} = 0.97$, $p_{gg} = .210$. The full ANOVA results for these analyses can be found in Appendix K.

Map Data-Pointing-equivalent Pairs: As with its contrast analysis counterpart, the results from this data set were very similar to those of the all map data. Error was significantly reduced by grouping objects semantically (M = 58.73º) as compared to the distributed organization (M = 68.42º), $F(1, 92) = 4.28$, $MSE = 1577.5$, $p = .041$. Quadrant pair type also had a significant effect, which was again consistent with the map data, $F(2, 184) = 6.49$, $MSE = 184.6$, $\varepsilon_{gg} = 0.95$, $p_{gg} = .002$. Similarly, no interaction of semantic grouping and quadrant pair emerged, $F(2, 184) = 1.35$, $MSE = 184.6$, $\varepsilon_{gg} = 0.95$, $p_{gg} = .261$.

Consistent with its matching contrast (c), no main effect of walls emerged, $F(1, 92) = 3.02$, $MSE = 1577.5$, $p = .085$. Walls did however, significantly interact with quadrant pair type, with the presence of walls reducing error to a greater degree for within quadrant pairs (M = 58.48º walls vs. 70.84º no walls) than it did for between lateral pairs (*M* = 54.99º walls vs. 64.27º no walls) and for between diagonal quadrant pairs (*M* = 65.05º walls vs. 67.84º no walls), $F(2, 184) = 3.1$, $MSE = 184.6$, $\varepsilon_{gg} = 0.95$, $p_{gg} = .050$. The full ANOVA results for these analyses can be found in Appendix L.

Free Recall of Landmark Names

Number Recalled: The first part of the landmark free recall analysis was an ANOVA examining the effect of walls and semantic grouping on the number of objects recalled. This analysis showed that the presence of walls (*M* = 13.5, *SD* = 1.82) did not significantly change the number of objects recalled compared to not having walls (*M* = 13.6, *SD* = 1.68), $F(1, 92) = 1.21$, $MSE = 3.09$, $p = .728$. Similarly, there was no difference in recall between those participants who saw semantically grouped objects (*M* = 13.63, *SD* = 1.68) and those who did not (*M* = 13.5, *SD* = 1.82), $F(1, 92) = 1.21$, $MSE = 3.09$, $p = .728$. No interaction between these two factors emerged either, $F(1, 92) = 1.21$, $MSE = 3.1$, $p = .728$. This shows that all conditions imparted roughly the same amount of landmark knowledge and that overall memory for the objects seen was high (overall *M* = 13.66 of the 16 landmarks, 85.4% recalled). See Appendix M for the full ANOVA output for this analysis.

Clustering: To analyze the clustering data I performed two 2 x 2 between-subjects ANOVAs; one for each type of clustering category (quadrant and semantic). I separated the two clustering types in this way to avoid problems with collinearity, due to the semantically grouped environments having their semantic categories organized by quadrant. The two run counts are therefore measuring the same thing for those conditions, which would create problems if analyzed together. The analysis of the quadrant category runs revealed no difference in the number of quadrant runs between those environments with walls (*M* = 9.58, *SD* = 2.144) and those without (*M* = 9.98, *SD* = 1.80), *F*(1, 92) = 0.96, *MSE* = 3.917, *p* =.330. There was however, an effect of grouping. Those conditions with objects grouped semantically (*M* = 7.77, *SD* = 2.05) had significantly fewer quadrant category runs (more clustering) than did those conditions in which the objects were not semantically grouped (*M* = 11.79, *SD* = 1.89). This was a large effect, *F*(1, 92) = 99.01, *MSE* = 3.917, $p < .001$. However, it should again be noted that quadrant category runs were confounded (by design) with semantic category runs for environments where categories were grouped by quadrant. This difference is shown in Figure 8. Therefore, this difference is really quadrant category plus semantic category runs versus quadrant category runs for the grouped versus the distributed conditions. The interaction of walls and semantic grouping had no significant effect on number of quadrant runs, *F*(1, 92) = 0.07, *MSE* = 3.917, *p* = .797.

The analysis of the semantic category runs revealed a similar pattern of results, although the effects were not as large. Again, no difference emerged in the number of semantic runs between those environments with walls (*M* = 7.79, *SD* = 2.144) and those without (*M* = 8.54, *SD* = 1.80), *F*(1, 92) = 3.86, *MSE* = 3.49, *p* =.052, although it was close to statistical significance. There was also an effect of grouping. Those conditions with objects grouped semantically (*M* = 7.77, *SD* = 2.05) had significantly fewer semantic category runs than did those conditions in which the objects were not semantically grouped (*M* = 8.56, *SD* = 1.67), *F*(1, 92) = 4.3, *MSE* = 3.49, *p* = .041. Again, the grouped condition had both semantic category and quadrant category runs versus only semantic category runs for the distributed condition. This difference in shown in the two left bars in Figure 8. The interaction of walls and semantic grouping had no significant effect on number of quadrant category runs, $F(1, 92) = 0.07$, $MSE = 3.917$, $p = .797$. Appendix N contains the full ANOVA output for this analysis.

Because clustering by quadrant was confounded with clustering by semantic category for those participants in the semantically grouped conditions, an additional analysis was performed which focused solely on the data from the distributed conditions (not semantically grouped landmarks). This was a repeated measures ANOVA that treated run category as a within-subject factor with two levels: semantic and quadrant. This analysis confirmed that there were significantly more quadrant category runs (M =10.02,) than there were semantic category runs (M = 8.17,), $F(1, 46) = 30.01$, $MSE = 2.75$, $p < .001$. This greater number of runs indicates less clustering by quadrant and shows that those participants in the distributed (not semantically organized) environments still prioritized semantics over quadrant grouping when they were recalling. This difference is shown in the two right bars in Figure 8. Once again, the presence of walls did not significantly influence the number of runs (M =8.65 for walls, M = 9.54 for no walls), $F(1, 46) = 2.94$, $MSE = 6.55$, $p = .093$. No interaction emerged between the type of run and the presence of walls either, $F(1, 46) = 1.86$, $MSE = 2.75$, $p = .669$. For the full output of this analysis, see Appendix O.

IV. General Discussion

The results showed dissociations among the dependent variables as well as commonalities. As discussed in the Introduction, the differences between sketch map retrieval, which is analogous to free recall, and directional pointing retrieval, which is analogous to cued recall of cue-target pairs, may be related to differences in retrieval processes. Given that participants' sketch maps and directional pointing results followed identical learning experiences, their differences would most likely arise from differences in retrieval that depend on the type of retrieval task (sketch map production vs answering queries about paired objects).

Previous results have shown that sketch maps and directional pointing are highly correlated across a wide range of different experimental conditions, all of which had walls or wall-like structures as structural organization and compared directional pointing with pointing-equivalent sketch map pairs (Douglas & Colle, 2010). However, sketch map data consistently had smaller angular error (better performance) than equivalent directional pointing. Hoelscher and Colle (2014) showed that this sketch map advantage was eliminated when participants were restricted from self-cueing as they drew their maps because they could only put two landmark objects on each map. In addition, Knipper and Colle (2014) examined movies of how participants sketched maps and they found that their recall was organized. First putting down structural information such as walls and then putting down landmark objects systematically. Sketch map retrieval allows participants to control both spatial and temporal aspects of reproduction. In contrast, the directional pointing measure uses cue-target queries based on object names. Queries such as: imagine that you are standing in front of and squarely facing the _____ landmark at an arm's length away, point to where the _____ landmark would be. These cue-target pairs are presented to participants randomly, limiting their control over landmark object-to-object relationships. Their responses are also different. They mark an angle on a circle with one instead of placing and orienting a square on a 2-D plane with another. These pointing queries may also have more of a verbal emphasis than the sketchmap task, given that the cue-target queries are only presented verbally. These potential retrieval processing differences may be relevant to the dissociations that were found in the results.

In addition, it is important to note that I am using the nearly significant findings seen in both the pointing data and the map data-pointing-equivalent pairs as support for several of the proposed explanations below. I felt that the use of these nearly significant results was justified because they reflect the significant findings of the map data, and they appear consistently across both the contrasts and the ANOVAs. As I have mentioned before, the pointing data and the map data-pointing-equivalent pairs were calculated from many fewer object pairs than the all map data was, and so they have less power. Therefore, we have decided to proceed under the assumption that those nearly significant effects do indeed reflect meaningful differences.

The Effect of Semantic Grouping

The first finding of note was the effect of semantic organization, which was important for both environments with walls and without walls, but not in the same way. For those data sets that used sketchmap data (the all map data and the map data-pointing-equivalent pairs), semantic grouping was only effective at reducing error when walls were present. A potential explanation for this may be related to the fairly uniform distribution of objects in the environment. As a reference, Figure 9 shows the layout when objects were grouped semantically.

As a result of our random object placement method, a number of objects ended up near the boundaries between the quadrants. Such an arrangement likely did not matter when walls were present, as the walls created obvious divisions between the quadrants, and there would therefore have been little chance of forming groups between objects across quadrant borders. When walls were absent however, objects close to the boundaries could have formed ad-hoc groups due to their spatial proximity, such as the sofa and hunting game or the cluster of coffee, Gatorade machines, and dresser seen in Figure 9. The formation of these ad-hoc groups could then have competed with the semantic grouping during recall, which would explain why semantic grouping did not reduce error without walls. For example, a participant could have formed ad hoc goals such as Barselou (1983) suggested by thinking about scenarios such as: “I got a coffee for me and a Gatorade drink for my friend and put them on the dresser for our lunch.”

The directional pointing data however showed that semantic grouping was beneficial both for conditions with walls and those with no walls. In the latter case (no walls) the effect of semantic grouping was limited to only within quadrant pairs. As mentioned previously, this difference from the results seen with sketchmap measure was a likely product of the different retrieval tasks required by the two measures. It is however not yet clear how retrieval processing in the directional pointing task would affect semantic grouping in this way.

Regardless of the reason for the differential effect of semantic grouping on these two types of measures, it is clear that such grouping had significant influence on both.

This is consistent with the prediction that semantic grouping would improve recall of spatial information. The fact that verbal/linguistic categorization was able to influence the recall of configural/spatial knowledge is also consistent with the comparable processing assumption of OBSERVE theory, which formed the basis for that prediction (Colle, 2018). Conversely, these effects are not easily accounted for by metric coordinate framework theories, as semantic information should not be relevant to the plotting of locations in a coordinate system.

The Effect of Walls

The difference between walls versus no walls was also important, but not universal. Once again, the all map data and the map data-pointing-equivalent pairs had similar results, with walls reducing angular error relative to no walls. Additionally, both data sets showed an interaction of walls with pair type (within versus between). It seems that when walls were present, error was roughly equal for within quadrant pairs and between quadrant pairs. The error for both of these groups rose when walls were absent, but this increase in error was significantly more pronounced for the within quadrant pairs than the between-quadrant pairs. One potential explanation for this pattern is that when participants place landmark objects on their map, a given amount of lateral displacement will produce more angular error for a pair of objects that are close together than it would for a pair that is separated by a greater distance. Errant lateral object placement is less likely to be manifested when walls are present because the walls would serve as proximal cues constraining where both objects are placed. When walls were absent however, these constraints would be absent, allowing for increased angular error for the closer within quadrant pairs relative to their more distant between-quadrant counterparts.

However, the directional pointing data was an exception to the pattern found with the sketch map data. Angular error when walls were present was not significantly different from when walls were absent. This result was surprising. However, it is likely a consequence of Hoelscher and Colle (2014) finding that directional pointing was less context-sensitive than sketch map data. Structural features such as walls are not focal objects; they provide a context for focal landmark objects. This reduced context sensitivity may mean that walls cannot effectively be used as cues when responding to pointing queries. If so, then it may explain why the loss of the walls did not affect performance on the directional pointing task. In addition, directional pointing only asks participants for angles, not for placement on a plane, which may affect their perspective in retrieval, especially because without walls they may have also been able to perceive more ad hoc landmark object relationships. The current data cannot clarify these potential retrieval processes.

Though it is unclear why walls do not seem to have an effect on recall during the directional pointing task, it certainly influenced recall during the sketch map production task. This effect is consistent with the OBSERVE theory, which allows participants to use organizing structures as superordinate cues to which landmark objects can be spatially related. Metric coordinate framework theories expect that walls would reduce angular error, as perpendicular walls form local axes with which to orient and define a local coordinate system (Meilinger, 2008; Meilinger, Riecke, & Bülthoff, 2010; Wagner, 2006). However, it is important to note that all the experimental conditions showed that participants' angular error was better than chance level (90º) when walls were absent ($M_{\text{sketch map}} = 68.20º$; $M_{\text{pointing}} = 75.53º$). Thus, participants gained substantial configural spatial knowledge even when they had no obvious environmental coordinate systems on which to depend, given that there were no walls and landmark objects were randomly placed and randomly oriented on a homogeneous surface that extended so that the edges were not visually encountered during navigation. This is problematic for metric coordinate framework theories, which hold such a coordinate space is a requirement for learning spatial information (Levinson, 1996; Meilinger, Riecke, & Bülthoff, 2010; Wagner, 2006; Zhang, 2014). However, these results could also be tested with other types of boundaries, such as circular or triangular rooms.

Conclusions

The purpose of this experiment was to examine whether semantic organization can impart configural spatial knowledge when the environment contains no or only minimal spatial structure, especially the type of spatial structure that is considered to be important for spatial frameworks (e.g., walls). To this end both the presence of that structure and of semantic organization within otherwise identical environments were manipulated. Strangely, the two different measures employed returned different patterns of results. The results from sketch map measures indicated that organizing objects semantically improved the recall of configural spatial knowledge only when spatial structure was present. However, this finding may be partly the result of the randomized object placement enabling the formation of inter-category, spatially ad-hoc groups when walls were not present to segregate them. In addition to facilitating the effects of semantic grouping, walls were also shown to generally improve the recall of spatial knowledge, particularly for pairs of objects within a single quadrant. By contrast, the directional pointing data found semantic organization to be effective regardless of the presence or absence of walls, though in the latter case it was only for those pairs of objects within the same quadrant. Also, there did not appear to be any influence of walls on directional pointing results.

The fact that these two measures of configural spatial memory returned such different patterns was unusual, as past research has demonstrated that they correlated quite highly with one another for environments with walls or boundaries present (Douglas & Colle, 2010). It is notable that the two configural spatial memory measures differed most greatly in the present results when walls were absent. Although the two spatial measures are highly correlated for a wide variety of conditions, mean angular error has been found to be consistently smaller (better) for sketch map measures than for directional pointing measures (Douglas & Colle, 2010). This difference has been found to depend on what participants are allowed to put on their sketch maps. The sketch map advantage is found when they are allowed to draw in walls or to put all the object on the map together, but mean angular error for sketch maps was not statistically different from mean angular error from directional pointing when only two objects could be placed on blank paper at once (Hoelscher & Colle, 2014). The implication was that the context of walls or other the concurrent presence of other landmark objects provided structural context that aided memory retrieval.

The dissociation of the two measures of configural spatial memory in the present results suggests that the retrieval mechanisms required by these two measures may be differentially sensitive to structural elements of the environment. Participants in the present experiment were told to put all 16 landmark objects on one map, which Hoelscherr and Colle (2014) showed produced lower angular error compared with pointing. The present results also showed that angular error was smaller for sketch maps than for directional pointing ($M_{sketch\ map}$ = 63.50º; $M_{pointing}$ = 72.15º), suggesting that the sketch map measure is more sensitive to structural context than the directional pointing measure.

Despite these differences, two other findings were quite interesting. First, one of these came from the recall results, which showed that participants in all conditions recalled roughly the same number of landmark objects and that this amount was quite high. This is important because past research has demonstrated that angular error was affected by landmark recall, such that participants with less landmark recall also had higher angular error (Rizzardo, et al, 2013). Thus, the current recall results indicate that any differences in angular error between the current conditions were unlikely the result of differences in landmark knowledge, but instead reflect differences in configural spatial knowledge. When combined with the fact that semantic grouping can reduce error, this suggests that organizing landmarks semantically did not make them more memorable as landmark knowledge, but rather facilitated the spatial relations of those landmarks with one another, improving their configural spatial knowledge

Second, participants in all conditions performed better than chance, even when their environments had no walls. With the only information being visual experience of sixteen randomly distributed and randomly oriented objects in an otherwise featureless plane, they were still able to learn configural spatial information from what they saw during a 7-minute random navigation.

These two points suggest that our spatial cognitive processes are more flexible than traditional metric coordinate framework theories would allow. The present approach to studying spatial memory obtained from navigating “large-scale” environments (those not entirely viewable from a single location), is in its infancy. However, the results clearly suggest that the interactions of verbal with spatial knowledge are a potentially fruitful direction for clarifying human spatial knowledge acquisition and retrieval.

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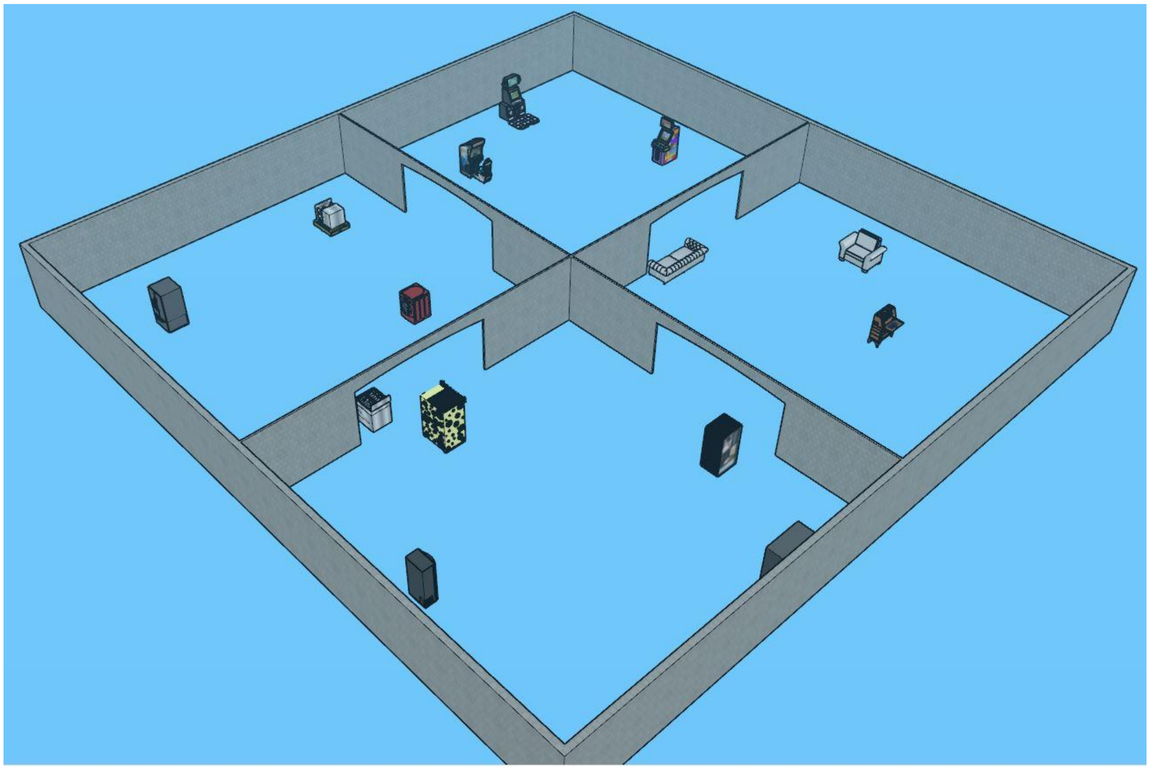


Figure 1. An angled view of the walled version of the environment seen from above.

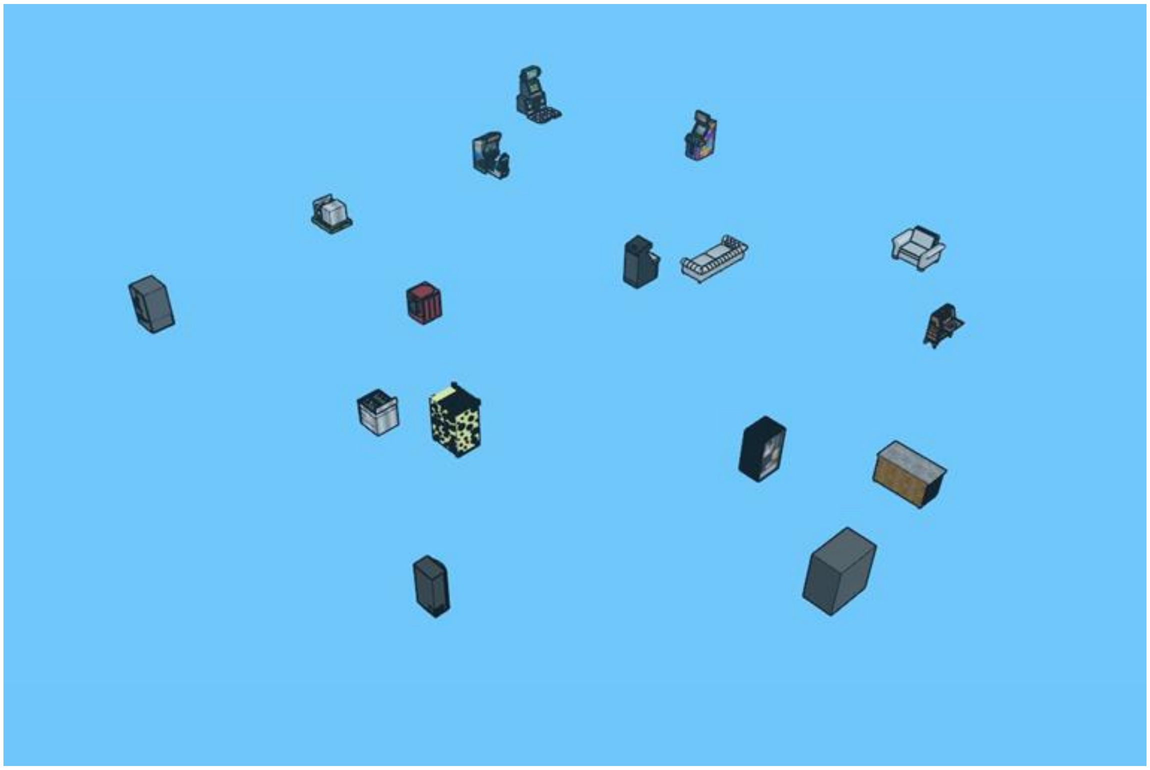


Figure 2. An angled view of the no-walls virtual environment seen from above.

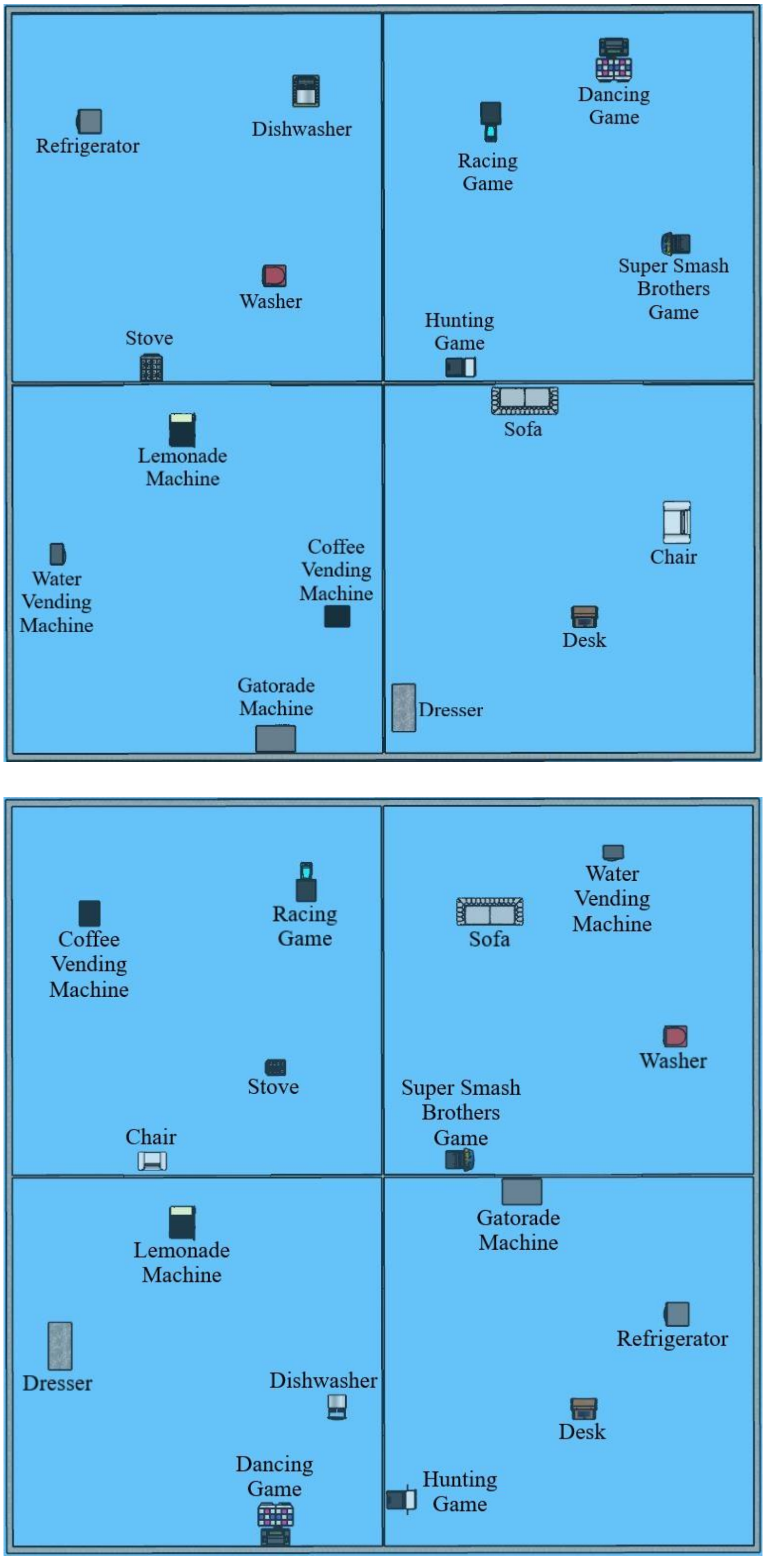


Figure 3. Object placement diagrams for both semantically grouped (top) and semantically distributed (bottom) object configurations.

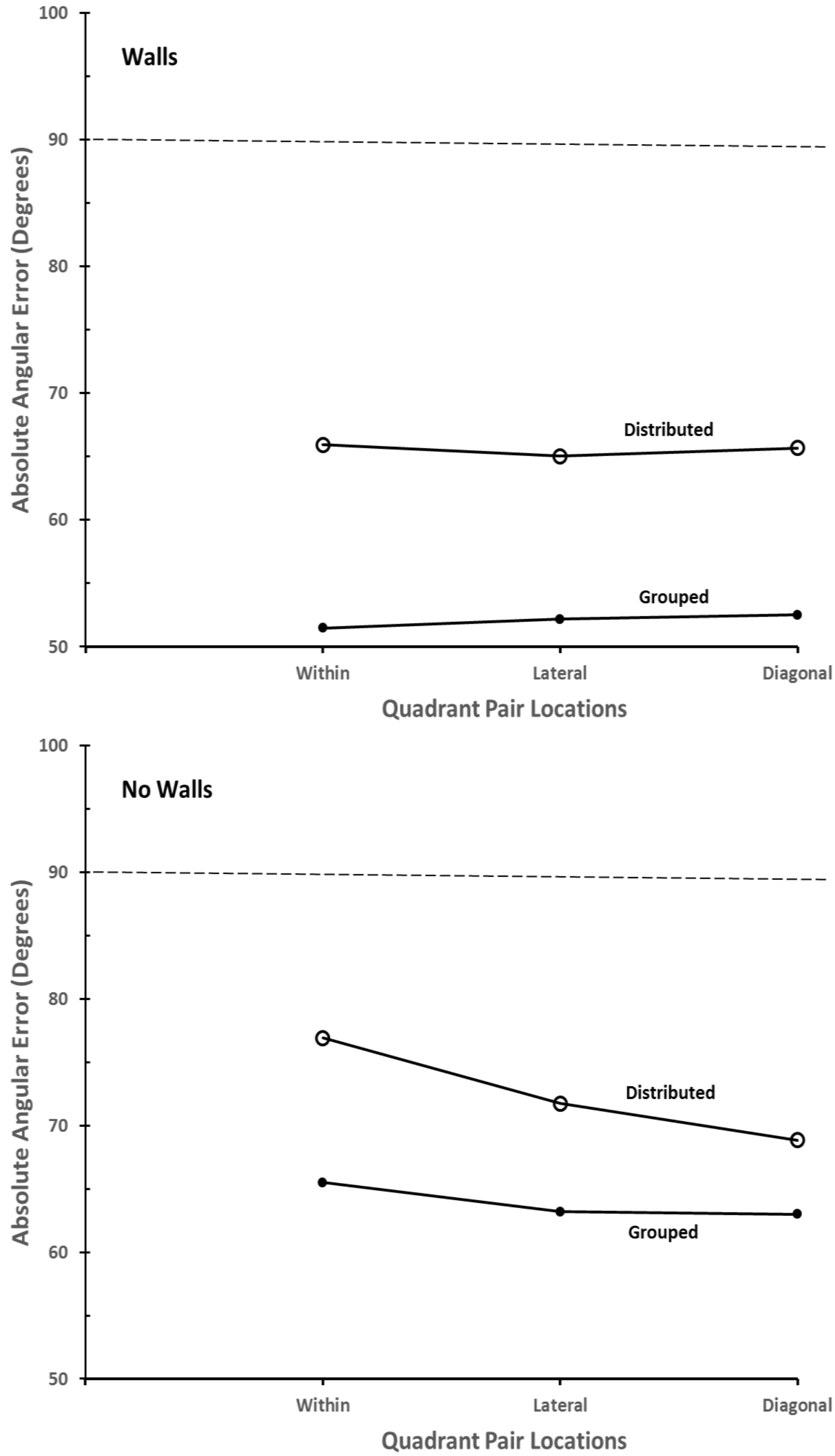


Figure 4. Comparison of sketch map data angular error when walls were present (top) and when walls were absent (bottom). The dashed line represents chance performance.

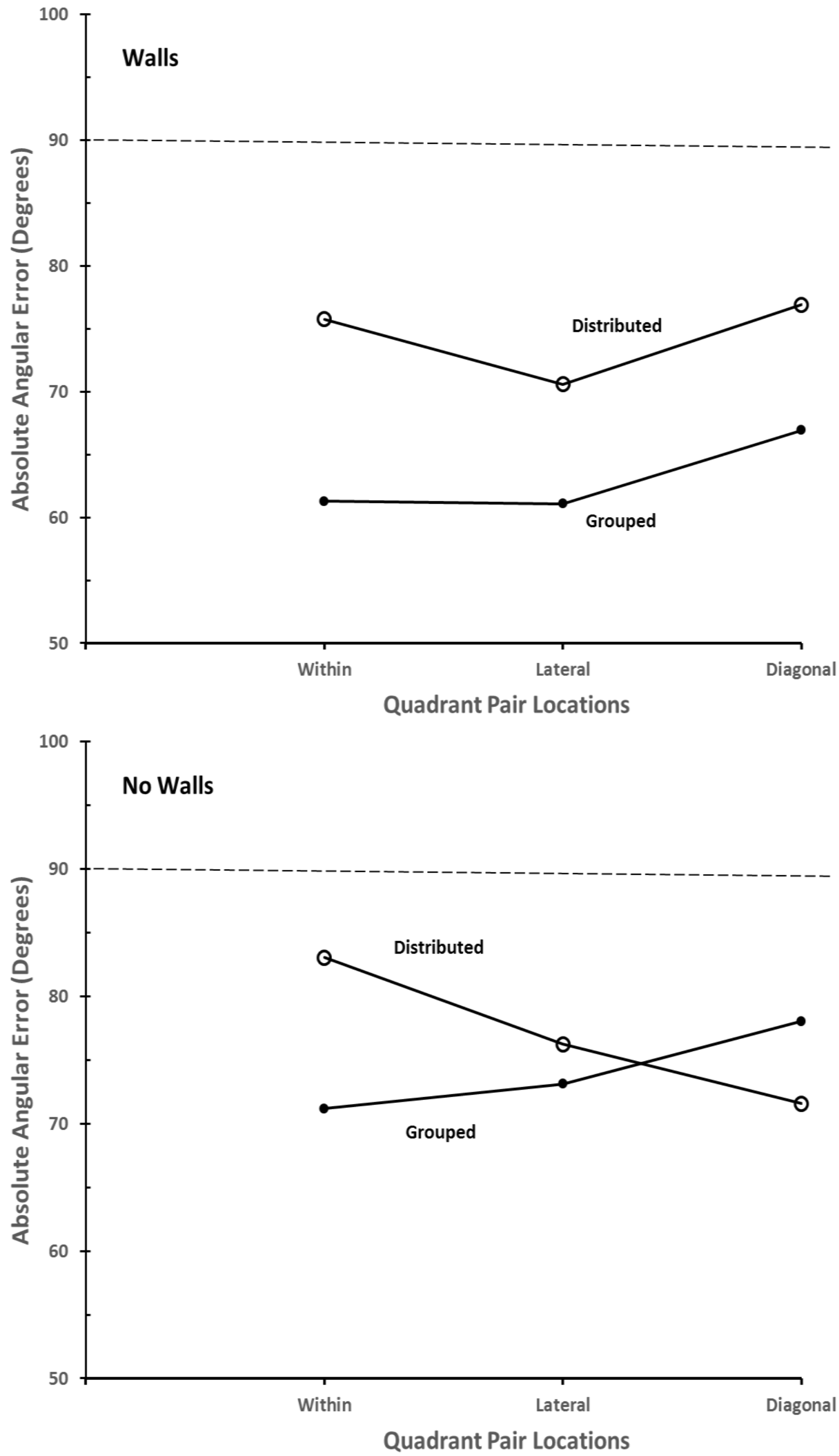


Figure 5. Comparison of pointing data angular error for semantic organization and quadrant pair types for walls (top) and no walls (bottom) conditions. The dashed line represents chance performance.

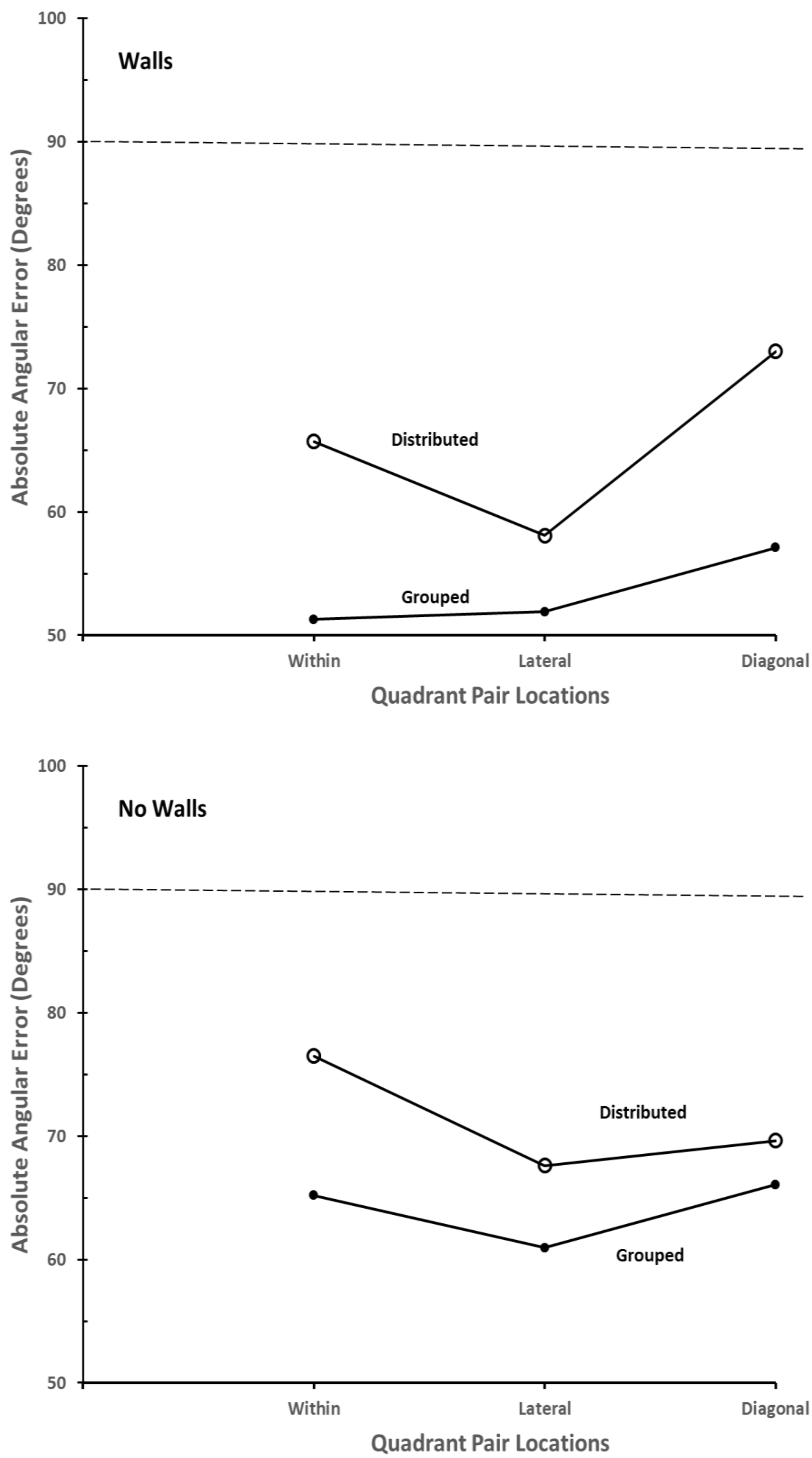


Figure 6. A comparison of the sketch map pointing-equivalent angular error with walls (top) and without walls (bottom). The dashed line represents chance performance.

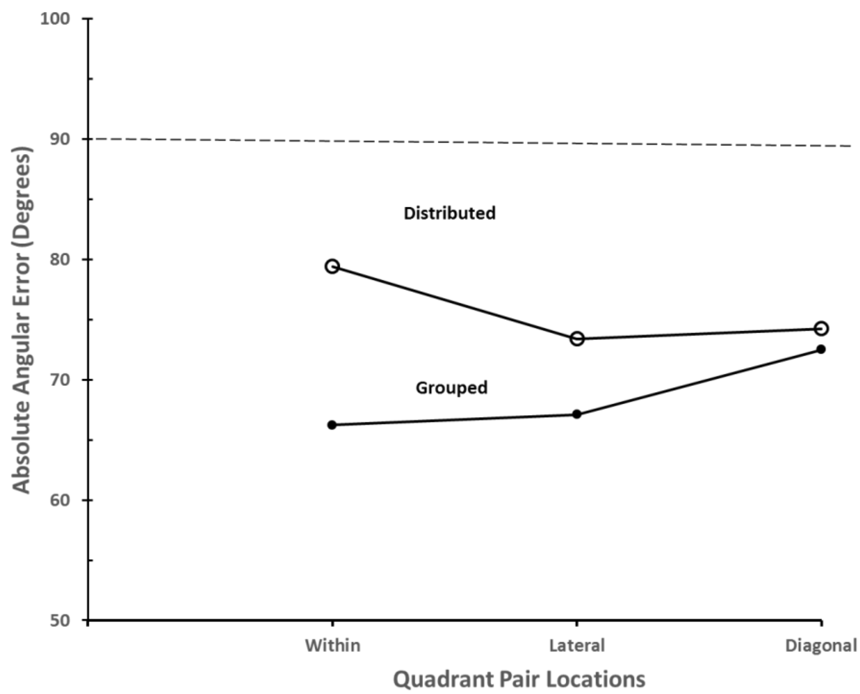


Figure 7. The interaction of quadrant pair type and semantic grouping for the directional pointing data. The dashed line represents chance performance.

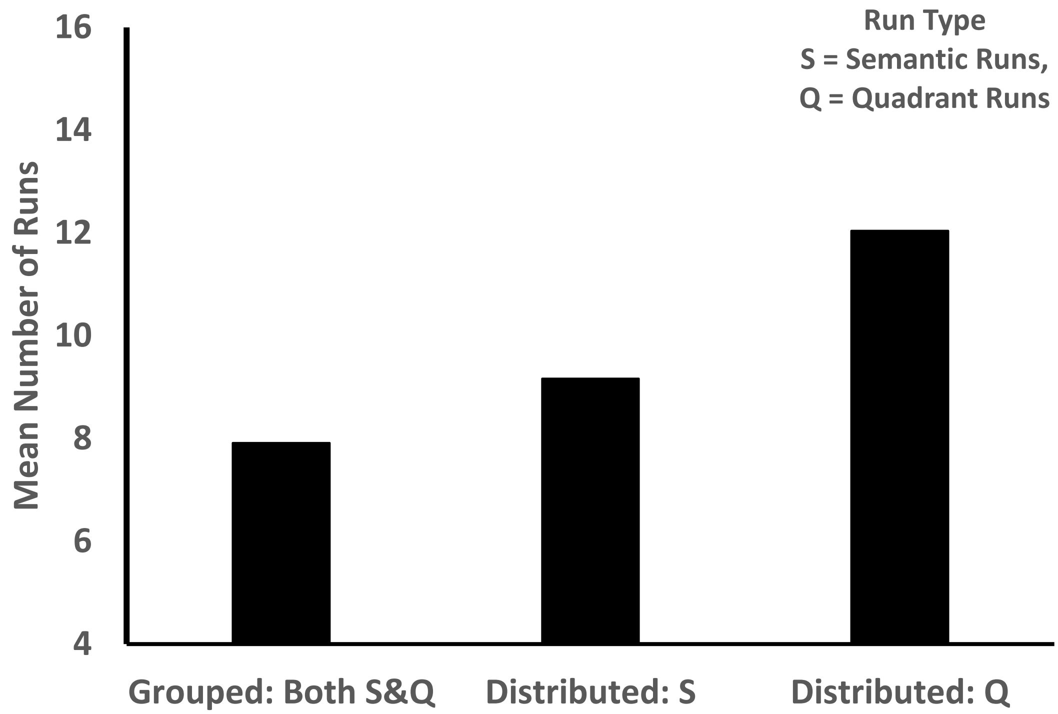


Figure 8. A comparison of run type differences for the two distribution conditions.

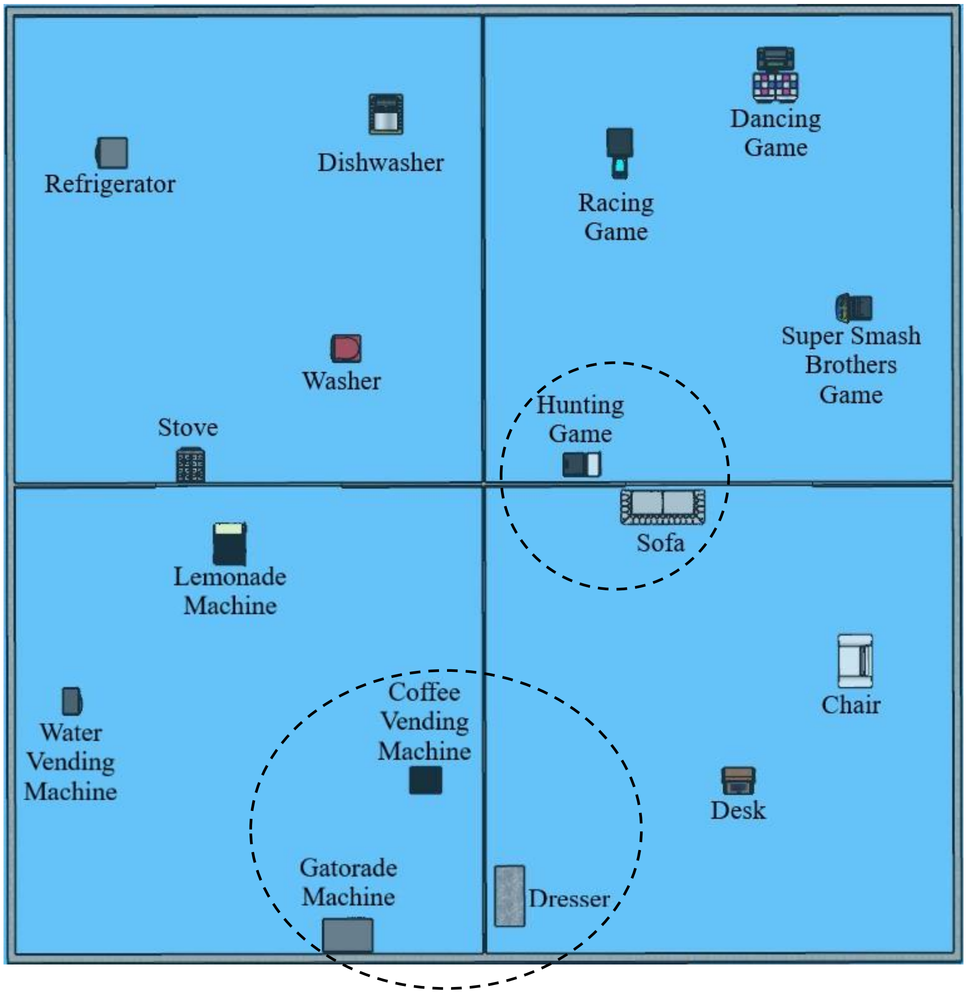
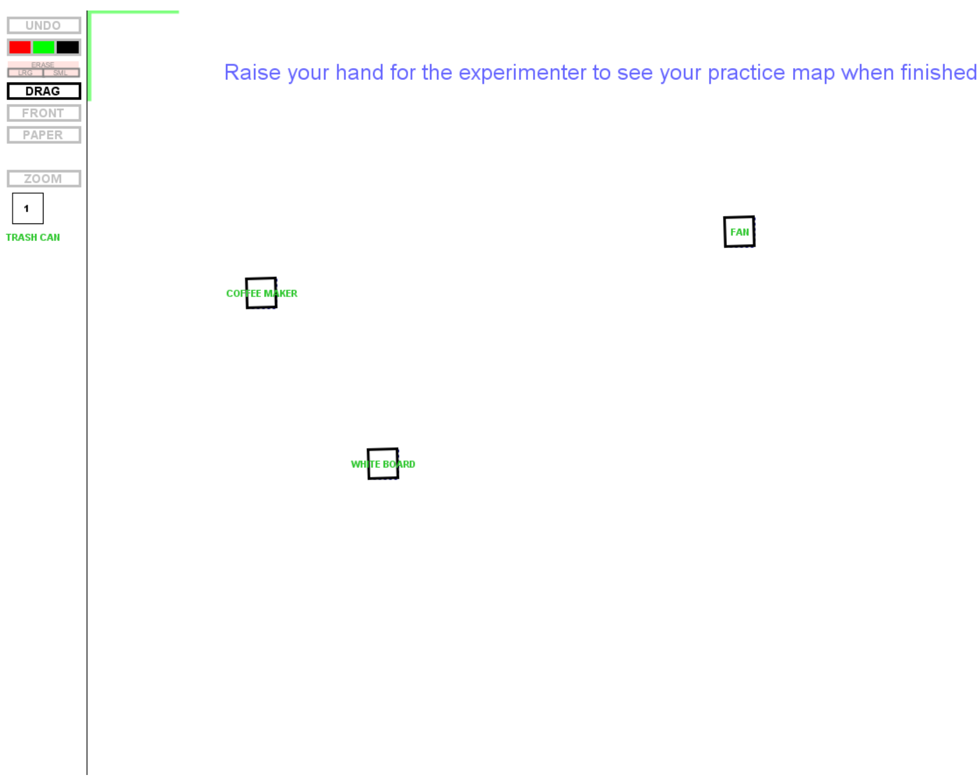


Figure 9. Object layout with semantic category grouping by quadrant. Two example cross-quadrant, possible ad-hoc groups, have been circled.

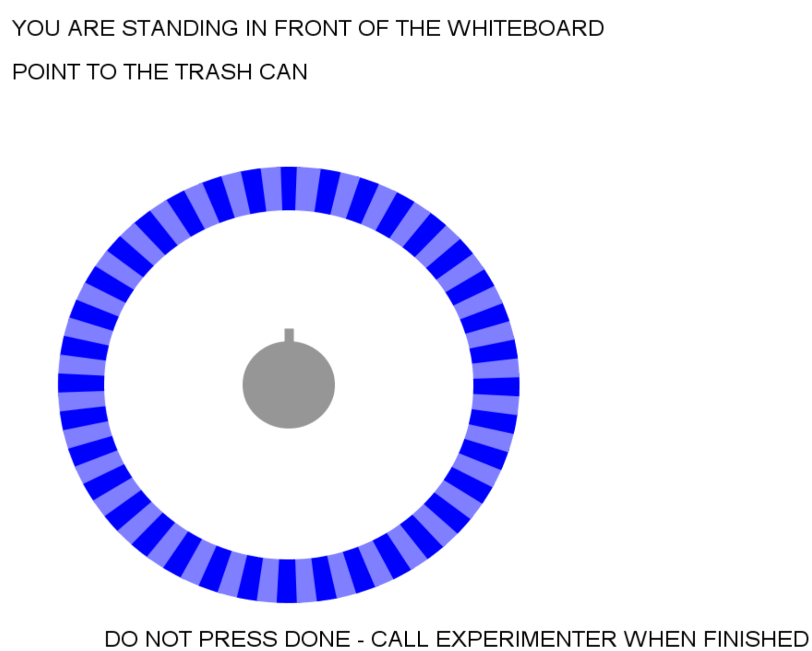
Appendix A

Sketchmap and Directional Pointing Details

Sketchmap: The commands relevant to this experiment consist of the DRAG, FRONT, and PAPER commands. The DRAG command is used to place each object by clicking and dragging a box from the sidebar to the desired location on the screen, choosing an object name from the sidebar list and dragging that name to the box, which it will snap to when released. To place an object on their sketchmap, participants chose the Drag command button and then touch the pen to the objects-remaining square to retrieve a movable box and drag it to the sketch map area. A number in the square on the sidebar displays the number of object boxes still needed to be added to the sketchmap, and this number is reduced by one after each object is placed. Each object box is square with sides of 0.952 cm (35 pixels). The Drag command is also needed to move object names from the list in the sidebar and attach them to objects they have placed on the sketch map. When a name is released onto one of the objects, it snaps to the middle of the object box. Participants can move the objects and change object labels at any time after they are placed in the map. After placing and naming all the objects, participants must then use the FRONT command to denote the front face of each object; the side where they had stopped during the tour and viewed the object from. Selecting a front is done by simply tapping the desired face of the box while the front command is active. This will turn that side of the box red to show it has been selected. Tapping another face of the box will color the new selection red and return the previous selection to black. Lastly, the PAPER command is used if the participant needs more space than a single screen would allow. After selecting it, the participant can click anywhere on the map and drag to move the viewable area as though one was dragging a large sheet of paper to reach a blank portion of it. This allows participants to place their objects at whatever scale they feel is appropriate. A screenshot of the shetchmap program in use can be seen below, displaying three of the four practice trial objects in testing room on the map and the trash can remaining to be placed on the sketch map.



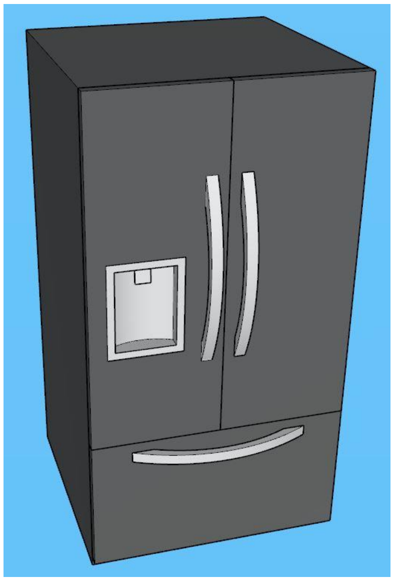
Directional Pointing: In this program, an electronic direction circle is used to make a series of Object Based Judgments (OBJs). To make these judgments participants are told to imagine a scenario in which they are squarely facing a given object from an arm's length away, and that they should now point to some target object. An example: "You are standing in front of the rocking chair. Point to the dog house." Thus these scenarios form a measurable angle, with the participant as the vertex, the direction they face as zero degrees "north", and the direction they indicate by pointing as the other ray. The pointing direction is measured using the direction circle, which is divided into 5 degree intervals and contains a top-down representation of a person's head at its center representing the participant (see image below). From this central position and imagining the object they face being at the top of the wheel (0 degrees), they then click on the 5-degree segment that would best align with their imagined pointing finger. Using the pen or mouse to select a chosen segment will change that segment's color to red to show they have made a selection. They can change their response if they wish by simply selecting a different segment. If they are satisfied with their selection to a query, then they can tap the DONE button that appears in the lower left corner of the screen to continue. Doing this will remove the old query and their selection, but a new query will not appear until they then tap on the gray circle in the center.



Appendix B

Landmark Object Images By Semantic Categories

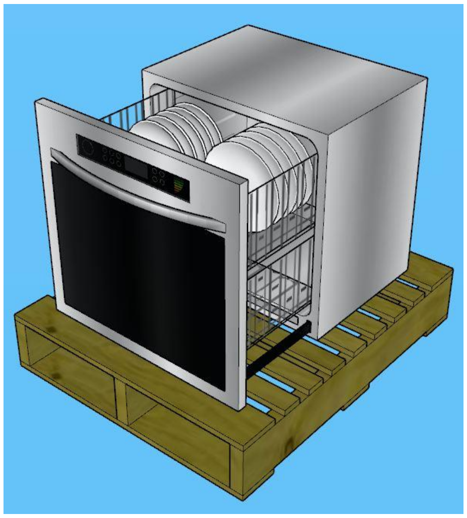
Appliances category



Washer (above) and Stove (below)

Refrigerator (above) and dishwasher

(below)



Games Category

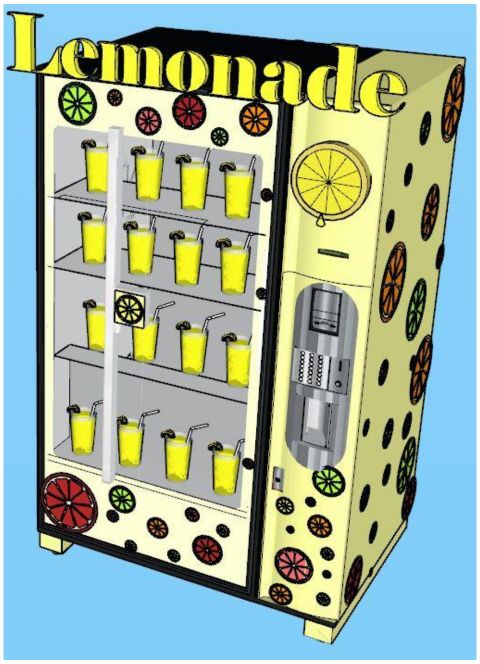
Dancing Game (above)

Super Smash Brothers Game (above)

Racing Game (below)

Hunting Game (below)

Beverage Vending Machine Category



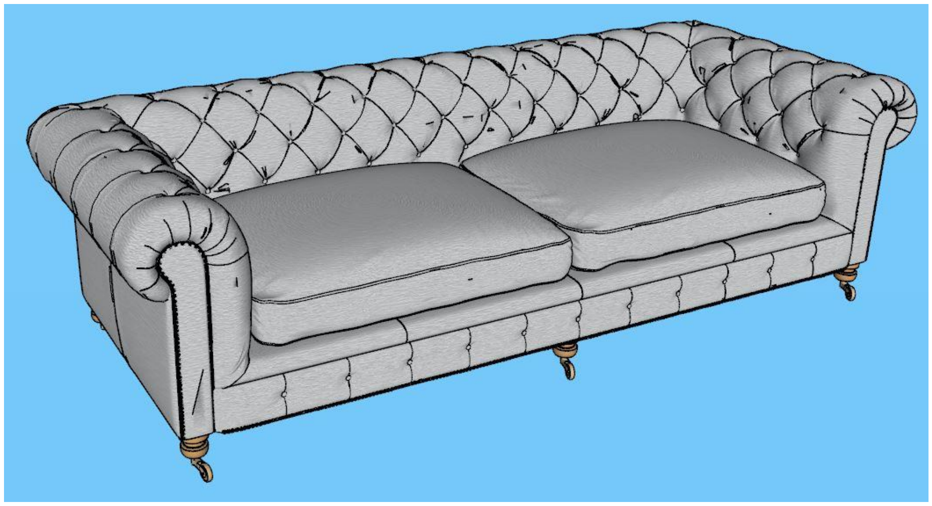
Lemonade Machine (above)

Water Vending Machine (above)

Coffee Vending Machine (below)

Gatorade Machine (below)

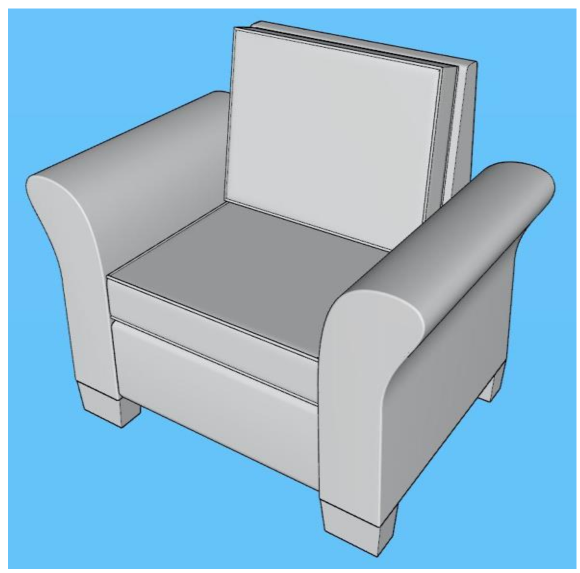
Furniture Category



Sofa (above)

Desk (below)

Armchair (below)



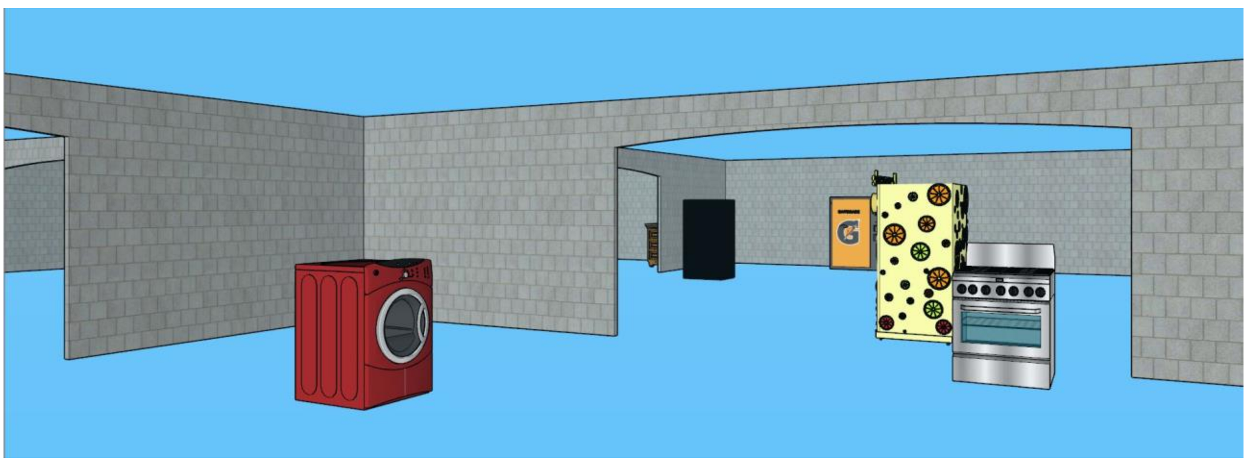
Furniture Category continued

Dresser

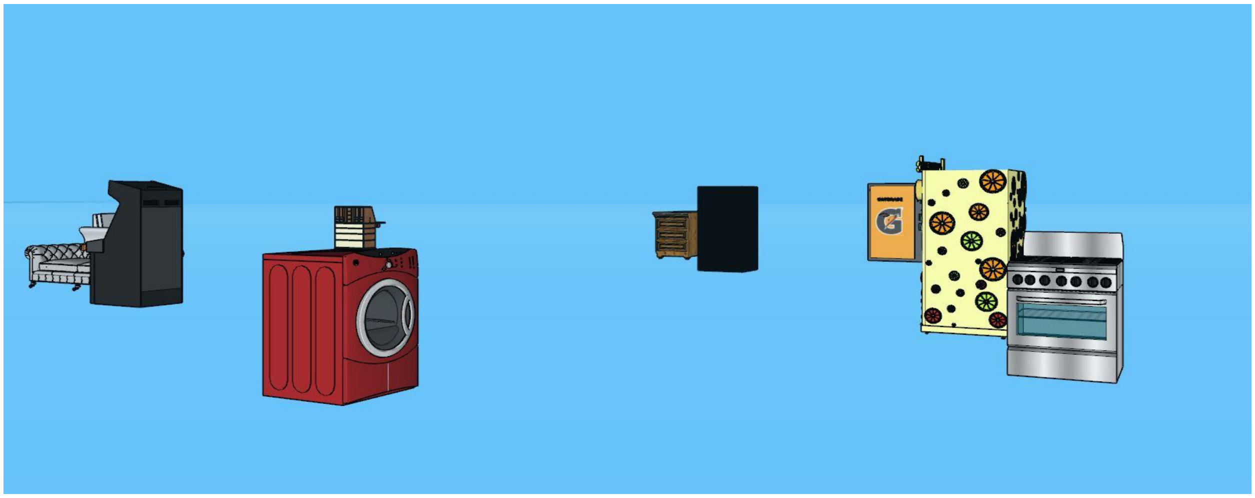
Appendix C

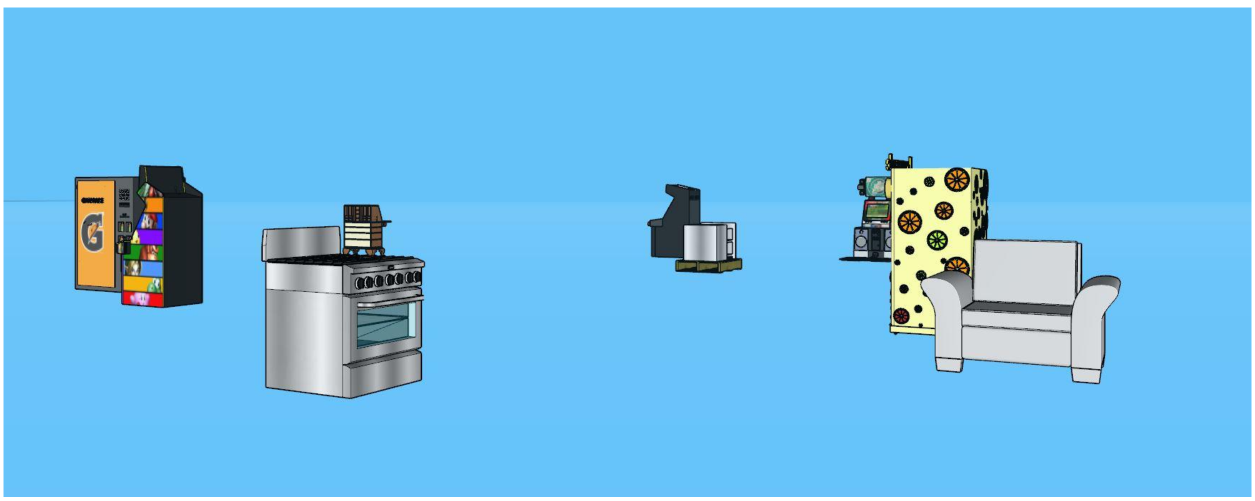
Point of View Environment Images

Below you can see identical, in-navigation viewpoints of the walled, semantically grouped environment (top) and the walled, distributed environment (bottom). The same views can be seen on the next page, without walls.



Below you can see identical, in-navigation viewpoints of the semantically grouped environment (top) and the distributed environment (bottom) when there are no walls.





Appendix D

Participant experiment briefing script

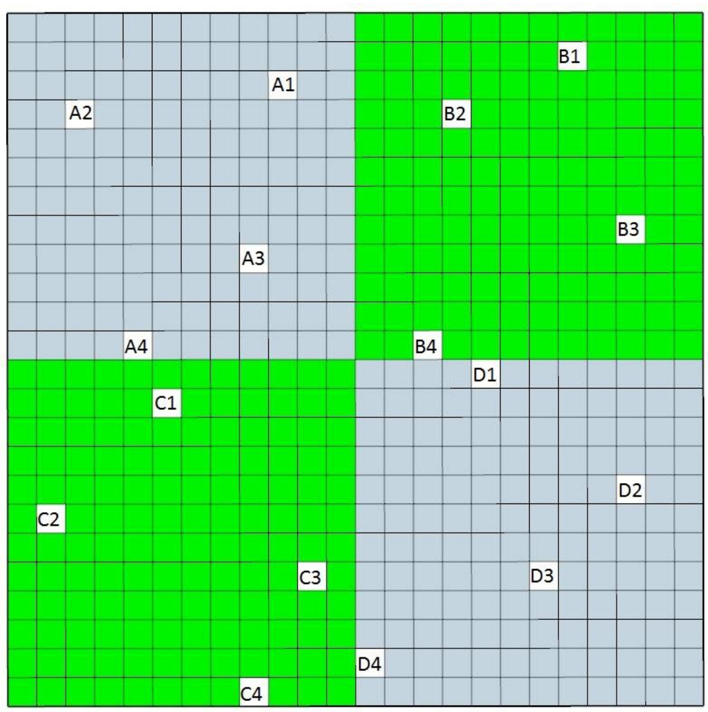
The following script is read to the participants once they are all seated at their computers, prior to starting the video navigation of the environment.

> Thank you all for coming.
>
> In this experiment you will watch a short video and will then be tested on what you saw. When you are watching the video, I would like you to imagine the following scenario:
>
> *You are a warehouse worker who has been asked to inventory a set of new items that have come in. In order to be sure you find all of them, you will be following the order on your inventory list, and checking them off one at a time. Because they were delivered at different times and by different people, they have not been organized well, so you will have to wander around to find each of them in the correct order.*
>
> During the video you will hear audio describing the items you are looking for, and verifying them when you reach each one.
>
> Please do not speak or make noise during the experiment or video. If you have a question, raise your hand and I will come speak with you. It is important that you pay attention to what you see during the video.
>
> Do you have any questions now before we begin?
>
> Please put on your headphones; they are the ones to your right.

Appendix E

Navigation Order of Visiting Landmark Object Locations

Visitation Order	**Grouped**	**Distributed**	**Location**
1	Washer	Stove	A3
2	Water Vending Machine	Dresser	C2
3	Dancing Game	Water Vending Machine	B1
4	Dresser	Hunting Game	D4
5	Lemonade Machine	Lemonade Machine	C1
6	Super Smash Brothers	Washer	B3
7	Stove	Chair	A4
8	Refridgerator	Coffee Machine	A2
9	Hunting Game	Super Smash Brothers	B4
10	Coffee Machine	Dishwasher	C3
11	Racing Game	Sofa	B2
12	Sofa	Gatorade Machine	D1
13	Desk	Desk	D3
14	Dishwasher	Racing Game	A1
15	Chair	Refridgerator	D2
16	Gatorade	Dancing Game	C4



Appendix F

Orthogonal Contrasts Table

		Walls						**No Walls**					
		Distributed			**Grouped**			**Distributed**			**Grouped**		
Contrast		**Within**	**Lateral**	**Diagonal**	**Within**	**Lateral**	**Diagonal**	**Within**	**Lateral**	**Diagonal**	**Within**	**Lateral**	**Diagonal**
DvG: Walls	a	1	1	1	-1	-1	-1	0	0	0	0	0	0
DvG: No Walls	b	0	0	0	0	0	0	1	1	1	-1	-1	-1
Walls v NoWalls	c	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1
Within v Btwn	d	1	-0.5	-0.5	1	-0.5	-0.5	1	-0.5	-0.5	1	-0.5	-0.5
Lateral v Diag	e	0	1	-1	0	1	-1	0	1	-1	0	1	-1
	a x d	1	-0.5	-0.5	-1	0.5	0.5	0	0	0	0	0	0
	b x d	0	0	0	0	0	0	1	-0.5	-0.5	-1	0.5	0.5
	c x d	-1	0.5	0.5	-1	0.5	0.5	1	-0.5	-0.5	1	-0.5	-0.5
	a x e	0	1	-1	0	-1	1	0	0	0	0	0	0
	b x e	0	0	0	0	0	0	0	1	-1	0	-1	1
	c x e	0	-1	1	0	-1	1	0	1	-1	0	1	-1

Note: The contrasts are:

Between-Subject Effects

a. Grouped semantic organization versus distributed organization with walls
b. Grouped semantic organization versus distributed organization without walls
c. Walls versus no walls

Repeated-Measures Effects

d. Within quadrant pairs versus between quadrant pairs (lateral & diagonal)
e. Between lateral quadrant pairs versus between diagonal quadrant pairs

Interactions

f. For walls only: Interaction of semantic grouping by within- versus between quadrant/room pairs
g. For No walls only: Interaction of semantic grouping with within- versus between quadrant/room pairs
h. Interaction of walls with within- versus between quadrant/room pairs
i. For walls only: Interaction of semantic grouping by between lateral- versus between diagonal quadrant/room pairs
j. For No walls only: Interaction of semantic grouping by between lateral- versus between diagonal quadrant/room pairs
k. Interaction of walls by between lateral- versus between diagonal quadrant/room pairs

Appendix G

Map All Data Contrasts ANOVA Table

	Contrast	SSQ MST	SSQ error	df	MS error	F	p	Partial η^2
DvG: Walls	A	6551.915	126366.4	92	1373.548	4.770067	0.0315015	0.049293
DvG: NoWalls	B	2666.598	126366.4	92	1373.548	1.941394	0.1668745	0.020666
WallsV No	C	6367.247	126366.4	92	1373.548	4.635621	0.0339305	0.04797
Within v Btw	D	306.0618	5559.562	92	60.43002	5.06473	0.0268003	0.052179
Lat v Diag	E	13.49101	1957.964	92	21.28222	0.63391	0.4279744	0.006843
	A x D	17.40195	5559.562	92	60.43002	0.287969	0.5928206	0.00312
	B x D	142.477	5559.562	92	60.43002	2.357719	0.1280964	0.024987
	C x D	347.454	5559.562	92	60.43002	5.749691	0.0185113	0.058821
	A x E	0.546417	1957.964	92	21.28222	0.025675	0.8730484	0.000279
	B x E	42.73394	1957.964	92	21.28222	2.007965	0.1598527	0.02136
	C x E	50.40282	1957.964	92	21.28222	2.368307	0.1272537	0.025096

Appendix H

Directional Pointing Data Contrasts ANOVA Table

	Contrast	SSQ MST	SSQ error	df	MS error	F	p	Partial η^2
DvG: Walls	A	4609.088	125977	92	1369.315	3.36598	0.0697878	0.035295
DvG: NoWalls	B	287.7303	125977	92	1369.315	0.210127	0.6477488	0.002279
WallsV No	C	3298.511	125977	92	1369.315	2.408876	0.1240824	0.025515
Within v Btw	D	65.12361	15729.55	92	170.9734	0.380899	0.5386469	0.004123
Lat v Diag	E	464.3867	20133.72	92	218.8448	2.121991	0.1486023	0.022545
	A x D	180.0304	15729.55	92	170.9734	1.052974	0.3075137	0.011316
	B x D	1466.007	15729.55	92	170.9734	8.574477	0.0042966	0.085255
	C x D	116.8638	15729.55	92	170.9734	0.68352	0.4105163	0.007375
	A x E	1.311657	20133.72	92	218.8448	0.005994	0.9384591	6.51E-05
	B x E	552.1584	20133.72	92	218.8448	2.523059	0.1156237	0.026693
	C x E	429.6659	20133.72	92	218.8448	1.963336	0.1645213	0.020895

Appendix I

Sketch map data-pointing-equivalent pairs contrasts ANOVA table

	Contrast	SSQ MST	SSQ error	df	MS error	F	p	Partial η^2
DvG: Walls	A	5338.055	145132.9	92	1577.532	3.383802	0.0690651	0.035476
DvG: NoWalls	B	1858.586	145132.9	92	1577.532	1.178161	0.2805667	0.012644
WallsV No	C	4769.555	145132.9	92	1577.532	3.023429	0.0854149	0.031818
Within v Btw	D	169.0413	13618.4	92	148.0261	1.14197	0.2880324	0.012261
Lat v Diag	E	2226.013	20357.1	92	221.2728	10.06004	0.0020594	0.09857
	A x D	91.62072	13618.4	92	148.0261	0.61895	0.4334597	0.006683
	B x D	307.5001	13618.4	92	148.0261	2.077338	0.1528959	0.022081
	C x D	640.3057	13618.4	92	148.0261	4.325628	0.0403241	0.044906
	A x E	567.2562	20357.1	92	221.2728	2.563605	0.1127773	0.02711
	B x E	57.29531	20357.1	92	221.2728	0.258935	0.6120709	0.002807
	C x E	504.3786	20357.1	92	221.2728	2.279442	0.134526	0.024178

Appendix J

Sketch Map All data of Factorial ANOVA table

Between Subjects Effects

	Sum of Squares	df	Mean Square	F	p	η^2_p
Walls	6367.2	1	6367.2	4.636	0.034	0.048
Distributed	8789.1	1	8789.1	6.399	0.013	0.065
Walls * Distributed	429.4	1	429.4	0.313	0.577	0.003
Residual	126366.4	92	1373.5			

Note. Type III Sum of Squares

Within Subjects Effects

	Sphericity Correction	Sum of Squares	df	Mean Square	F	p	η^2_p
Pair Type	None	319.55	2.000	159.78	3.911	0.022	0.041
	Greenhouse-Geisser	319.55	1.532	208.54	3.911	0.032	0.041
Pair Type * Walls	None	397.86	2.000	198.93	4.869	0.009	0.050
	Greenhouse-Geisser	397.86	1.532	259.64	4.869	0.015	0.050
Pair Type * Distributed	None	146.54	2.000	73.27	1.793	0.169	0.019
	Greenhouse-Geisser	146.54	1.532	95.63	1.793	0.178	0.019
Pair Type * Walls * Distributed	None	56.62	2.000	28.31	0.693	0.501	0.007
	Greenhouse-Geisser	56.62	1.532	36.95	0.693	0.465	0.007
Residual	None	7517.53	184.000	40.86			
	Greenhouse-Geisser	7517.53	140.975	53.33			

Note. Type III Sum of Squares

Appendix K

Directional Pointing data factorial ANOVA table

Between Subjects Effects

	Sum of Squares	df	Mean Square	F	p	η^2_p
Walls	3299	1	3299	2.409	0.124	0.026
Distributed	3600	1	3600	2.629	0.108	0.028
Walls ✻ Distributed	1297	1	1297	0.947	0.333	0.010
Residual	125977	92	1369			

Note. Type III Sum of Squares

Within Subjects Effects

	Sphericity Correction	Sum of Squares	df	Mean Square	F	p	η^2_p
Pair Type	None	529.5	2.000	264.8	1.358	0.260	0.015
	Greenhouse -Geisser	529.5	1.936	273.5	1.358	0.260	0.015
Pair Type ✻ Walls	None	546.5	2.000	273.3	1.402	0.249	0.015
	Greenhouse -Geisser	546.5	1.936	282.3	1.402	0.249	0.015
Pair Type ✻ Distributed	None	1586.6	2.000	793.3	4.070	0.019	0.042
	Greenhouse -Geisser	1586.6	1.936	819.4	4.070	0.020	0.042
Pair Type ✻ Walls ✻ Distributed	None	612.9	2.000	306.5	1.572	0.210	0.017
	Greenhouse -Geisser	612.9	1.936	316.6	1.572	0.211	0.017
Residual	None	35863.3	184.000	194.9			
	Greenhouse -Geisser	35863.3	178.132	201.3			

Note. Type III Sum of Squares

Appendix L

Sketch map data-pointing-equivalent pairs factorial ANOVA table

Between Subjects Effects

	Sum of Squares	df	Mean Square	F	p	η^2_p
Walls	4769.6	1	4769.6	3.023	0.085	0.032
Distributed	6748.1	1	6748.1	4.278	0.041	0.044
Walls * Distributed	448.5	1	448.5	0.284	0.595	0.003
Residual	145132.9	92	1577.5			

Note. Type III Sum of Squares

Within Subjects Effects

	Sphericity Correction	Sum of Squares	df	Mean Square	F	p	η^2_p
Pair Type	None	2395.1	2.000	1197.5	6.485	0.002	0.066
	Greenhouse-Geisser	2395.1	1.908	1255.2	6.485	0.002	0.066
Pair Type * Walls	None	1144.7	2.000	572.3	3.100	0.047	0.033
	Greenhouse-Geisser	1144.7	1.908	599.9	3.100	0.050	0.033
Pair Type * Distributed	None	499.4	2.000	249.7	1.352	0.261	0.014
	Greenhouse-Geisser	499.4	1.908	261.7	1.352	0.261	0.014
Pair Type * Walls * Distributed	None	524.3	2.000	262.1	1.420	0.244	0.015
	Greenhouse-Geisser	524.3	1.908	274.8	1.420	0.245	0.015
Residual	None	33975.5	184.000	184.6			
	Greenhouse-Geisser	33975.5	175.546	193.5			

Note. Type III Sum of Squares

Appendix M

Number of words recalled factorial ANOVA table

ANOVA – Total Words Recalled

Cases	Sum of Squares	df	Mean Square	F	p
Walls	0.375	1	0.375	0.121	0.728
Distributed	0.375	1	0.375	0.121	0.728
Walls ✻ Distributed	0.375	1	0.375	0.121	0.728
Residual	284.500	92	3.092		

Note. Type III Sum of Squares

Appendix N

Number of recall quadrant runs and semantic runs factorial ANOVA tables

ANOVA - #RunsQuadrant

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Walls	3.760	1	3.760	0.960	0.330	0.010
Distributed	388.010	1	388.010	99.055	< .001	0.518
Walls ✻ Distributed	0.260	1	0.260	0.066	0.797	0.001
Residual	360.375	92	3.917			

Note. Type III Sum of Squares

ANOVA - #RunsSemantic

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Distributed	15.042	1	15.042	4.301	0.041	0.045
Walls	13.500	1	13.500	3.860	0.052	0.040
Distributed ✻ Walls	5.042	1	5.042	1.442	0.233	0.015
Residual	321.750	92	3.497			

Note. Type III Sum of Squares

Appendix O

Free recall data factorial ANOVA tables for quadrant and semantic runs

ANOVA - #RunsQuadrant

Cases	Sum of Squares	df	Mean Square	F	p	η²
Walls	3.760	1	3.760	0.960	0.330	0.005
Distributed	388.010	1	388.010	99.055	< .001	0.516
Walls ✻ Distributed	0.260	1	0.260	0.066	0.797	0.000
Residual	360.375	92	3.917			

Note. Type III Sum of Squares

ANOVA - #RunsSemantic

Cases	Sum of Squares	df	Mean Square	F	p	η²
Walls near	13.500	1	13.500	3.860	0.052	0.038
Distributed	15.042	1	15.042	4.301	0.041	0.042
Walls ✻ Distributed	5.042	1	5.042	1.442	0.233	0.014
Residual	321.750	92	3.497			

Note. Type III Sum of Squares

Appendix P

Distributed only free recall data factorial ANOVA table

Between Subjects Effects

	Sum of Squares	df	Mean Square	F	p	η^2_p
Walls	19.26	1	19.260	2.940	0.093	0.060
Residual	301.40	46	6.552			

Note. Type III Sum of Squares

Within Subjects Effects

	Sum of Squares	df	Mean Square	F	p	η^2_p
Runs	82.510	1	82.510	30.009	< .001	0.395
Runs ✻ Walls	0.510	1	0.510	0.186	0.669	0.004
Residual	126.479	46	2.750			

Note. Type III Sum of Squares

Appendix Q

Chance Level Determination of Absolute Angular Error

As presented in the methods section, the absolute value of the angular difference for the angle between a pair of objects on the sketch maps, R_{ij}, and the comparable angle between the pairs in the simulated environment, T_{ij}, was calculated and used as the absolute angular error, E_{ij} (Batschelet, 1981). Equation 1 shows how the shortest error distance around the circle was calculated. The absolute angular error difference, E_{ij}, had a minimum of 0° (completely accurate), and a maximum of 180°.

$$E_{ij} = \text{Minimum} [\, | R_{ij} - T_{ij} | \, , 360 - | R_{ij} - T_{ij} | \,]$$

Because the probability distribution for E_{ij} is not circular and is uniform on the closed interval [0, 180], chance performance is an absolute angular error of 90°, as the mean and median of a uniform distribution is one half its range.