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Architecture of Mind and World: How Urban Form Influences Spatial Cognition

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Architecture of Mind and World:

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Abstract

We all require spatial knowledge of our environment. Many people spend the better part of their day in a built environment, and therefore, much of their thought about space is directly intertwined with the architectural and urban form of their surroundings. How does the form of people's surroundings affect their spatial knowledge? Tversky (1981, 1992) has demonstrated that people's spatial knowledge is systematically distorted by the use of heuristics to simplify alignment and rotation information. A set of computational techniques known as space syntax (Bafna, 2003) can be used to formally describe an environment. This study pairs such an analysis of a case study environment with results from spatial judgment and memory tasks. Findings suggest that space syntax measures significantly predict people's performance on those tasks.

Architecture of Mind and World:

How Urban Form Influences Spatial Cognition

We all require spatial knowledge of our environment in order to travel to the grocery store and back, in order to answer such questions as "Which is further west, Reno or San Diego?", and in order to provide route directions to visitors from out of town. How we acquire, store, and use this knowledge is of central interest to the field of spatial cognition. Many people spend the better part of their day in a built environment, i.e. the urban world (with varying density) of buildings, streets, parks, parking lots, blocks, and squares that has been designed and constructed by humans. Therefore, much of their thought about space (*spatial judgment and memory*) and movement through space (*wayfinding*) is directly intertwined with the architectural and urban form of their surroundings. How does the form of people's urban surroundings affect their spatial knowledge of those places? In particular, how does urban form affect spatial judgment and memory?

These questions, as well as the subject matter of spatial cognition more generally, are intimately connected with a number of other topics of study in the field of cognitive science. Spatial knowledge is commonly acquired through first-hand experience with an environment or through use of representations of that environment, such as maps. Taking in and perceiving this external information necessarily involves perception (usually visual or auditory). Moreover, in the case of first-hand experience, one's body acts in and moves through the surrounding environment. Thus, issues of embodied/embedded action and cognition arise in the study of spatial cognition. Here I will focus specifically on the interplay of urban form with spatial judgment and memory.

Studying the effects of urban form on spatial cognition requires a formal system for describing the built environment. Space syntax, a set of techniques for analyzing the configuration of building interiors as well as urban environments, allows for such a computational characterization (Hillier and Hanson, 1984 is considered the seminal work). This study will pair these space syntax analyses with behavioral data on spatial judgment and memory tasks.

Cognitive Maps, Spatial Judgment, and Spatial Memory

The term *cognitive map* effectively refers to the mental representations that store a person's spatial knowledge of an environment. However, the term is notoriously ambiguous – the form it takes on differs from theory to theory. Cognitive maps may be considered to be actual metric maps, map-like in form, acting like maps in practice, or convenient fictions (see Kitchin, 1994). For the purposes of this study, which focuses on performance in spatial judgment and memory tasks, I adopt the last view and simply consider a cognitive map to be one's spatial knowledge of an environment. According to this perspective, a cognitive map is shaped by a number of different processes that do not necessarily follow the constraints of physical maps.

Just as with most other processes of human thought, spatial cognition involves the use of heuristics. Tversky (1981) identified a set of basic heuristics that are used to encode and store memory of environments and maps, as well as of meaningless visual forms. "Remembering the absolute location of figures is difficult, and is facilitated by remembering locations relative to other figures and/or relative to the natural directions of the figure" (Tversky, 1981, p. 407). This simplification process is revealed in systematic errors, which Tversky attributes "to two heuristics that are derived from principles of perceptual organization” (1981, p. 407). The *alignment heuristic* predicts that “two figures that are perceived as grouped together but are misaligned, that is, offset in one spatial dimension, are remembered as more aligned than they really are.” The *rotation heuristic* assumes that “figures are remembered with respect to a frame of reference [e.g. north-south, east-west], and that, when the orientation of the frame of reference and the natural orientation of the figure conflict, the figure’s orientation will be remembered as closer to that of the frame of reference” (Tversky, 1992, p. 136). Note the connection to perceptual processes: rotation “is similar to the Gestalt organizing principle of common fate” and alignment “is related to grouping by proximity” (Tversky, 1992, pp. 135-6). These heuristics have been demonstrated to apply to the spatial judgment and memory of large-scale spaces, such as continents, more local spaces such as streets, and both real and artificial spaces that are learned through graphical representations like maps (see Tversky, 1992 for a review).

These alignment and rotation heuristics as well as other processes involved in spatial cognition lead to systematic errors in spatial judgment and memory (see Tversky, 1981, 1992 for reviews). For example, many incorrectly believe that San Diego is west of Reno, Nevada, due to the hierarchical grouping of cities within states and the subsequent alignment and rotation of the states. Tversky (2003) suggests a number of reasons that these errors exist. Cognitive processes schematize spatial information so that it can be represented and stored for future use. This schematization allows for integration of disparate knowledge from different sources and different perspectives as well as optimization of that knowledge so as to reduce the load on working memory. In the process of optimizing spatial knowledge, little metric information, e.g. distances, is precisely retained or preserved in whole. My proposal that the form of an environment is intimately connected with the form of its mental representation suggests that the use of these heuristics depends upon the configuration of the environment. The identification of systematic errors in spatial judgment and memory under specific conditions can be used to indicate the involvement of the alignment and rotation heuristics.

Space Syntax: Computational Analysis of Urban and Architectural Form

As previously mentioned, space syntax provides us with a set of techniques for producing an abstract model of the configuration of a building interior or a part of an urban area. The spaces in question are formally described in terms of their topology – in other words, in terms of the spatial relationships among those spaces, such as connections and adjacencies. Research in space syntax proposes that these models can represent and allow for analysis of salient social and cognitive aspects of building interiors and urban areas (Bafna, 2003). (For more on the philosophical assumptions of space syntax approaches, see Hillier and Hanson, 1984, and Hillier, 1996.)

This topological description takes the form of a graph indicating nodes and their interconnections. In one space syntax technique, *axial map analysis*, each of these nodes stands for a continuous line of sight in the environment. On the campus of Carleton College, one such sightline is the view down Winona Street running into Laird Hall (see the campus map in Figure 5). Such sightlines are commonly referred to as *axes* and a set of interconnected sightlines are called an *axial map*. As shown in the example of Figure 1, axes connect the various regions enclosed by obstacles, such as buildings that would block someone from seeing or walking through.

When creating an axial map, the researcher attempts to draw "the longest straight line" that will pass through the boundary between two adjacent regions of the environment in question (Bafna, 2003, p. 23). Thus the axes will connect with each other, forming a graph such as the one shown in Figure 2.

These graphs retain the topology of the axes—that is, the connections among the axes—but discard all metric information such as the length and angle of the axes. "The underlying intuition is… based on the notions that first, the line of sight is a significant organizing and unifying device in experience and that second, the number of distinct turns on a route are more crucial to spatial experience than actual distance covered" (Bafna, 2003, p. 23).

This "intuition" is in agreement with research in cognitive science. First, sightlines are a key component of J. J. Gibson's ecological theory of perception (see especially Gibson, 1979, Chapter 11). His "vistas" are centered by a person as opposed to the environment – your vista changes as your location changes – but both vistas and axes emphasize that at a particular moment in time we are presented with a limited view of our environment. When we move, our view progressively changes to reveal new regions, at the same time as we leave behind our most recent view. Our visual experience of the world is defined by this serial sequence of limited views.

Second, humans have been shown to be poor at estimating the metric distance of even the most familiar route or the angle formed by the best-known street intersections. Byrne (1979) has demonstrated that when people approximate distances, they rely on a heuristic that only considers the number of turns made on the route. When approximating the angle of street intersections, people are most likely to approximate the angle as nearly orthogonal (at right angles) or at 45-degree angles, a finding that suggests they are using Tversky's rotation heuristic.

Once an axial map has been created, measures can be performed on the graph of the axes. One such measure is *global integration*, which quantifies how well individual nodes (axes) are interconnected with the graph as a whole (the map) by calculating the average number of steps required to reach each node from every other node in the graph. Since highly integrated nodes can be quickly reached from many other nodes in the graph, they are described as "shallow," while less highly integrated nodes are "deeper" in the graph. In the example of Figure 1, Axis 3 has a high global integration value (8.30) while Axis 6 has a low global integration value (2.77). In Figure 2 it can be seen that Axis 3 is more highly integrated with the other nodes than Axis 6, which can only be accessed by way of Axis 7 and Axis 8.

While global integration measures properties of the graph as a whole, *local integration* only considers the connections among nodes in the context of their immediate surroundings. Local integration is usually computed with radius 3 – that is, only nodes within a radius of 3 are used when computing the integration for a particular node. Local integration values are given below each global integration value in Figure 1.

Integration measures have been found to accurately quantify various aspects of human behavior in the environment in question. Bafna (2003) cites studies in which the integration value of an axis in an urban setting was a significant predictor of the average number of pedestrians in that location—the higher the integration, the more pedestrians present. Haq and Zimring (2003) demonstrated such measures to be strong predictors of wayfinding behavior (where people walked) and abilities (how well they performed on assessments of their knowledge) inside large buildings, such as hospitals. Kim and Penn (2004) found that the integration values of street maps sketched by people correlate with actual integration values of the streets. In particular, local integration in the sketch maps correlated highly (r = .728) with local integration in the actual map. In other words, participants' spatial knowledge of the environment, as represented in their sketch maps, accurately represented the axial properties of the real world.

The space syntax measure of integration is closely associated with the concept of legibility proposed by Lynch (1960): "the ease with which [the cityscape's] parts can be recognized and can be organized into a coherent pattern. Just as this printed page, if it is legible, can be visually grasped as a related pattern of recognizable symbols, so a legible city would be one whose districts or landmarks or pathways are easily identifiable and are easily grouped into an over-all pattern" (p. 3). In the case of axial map analysis, such an overall pattern takes the form of a graph of axes. Integration measures how tightly each axis is knit into local groups (local integration) and the map as a whole (global integration).

Connecting Spatial Cognition and Space Syntax

Space syntax research suggests that places with certain configurational characteristics (i.e. higher integration) are used more frequently and by more people, are recalled more often by people, and are more accurately represented when recalled (Kim and Penn, 2004; Haq and Zimring, 2003). Spatial cognition research suggests that people perform better on spatial judgment and memory tasks for places that can be accurately schematized and integrated with other spatial knowledge (Tversky, 1981, 1992, 2003). I propose that there is an intimate connection between these features of the built world and of spatial judgment and memory. Accordingly, space syntax measures, such as integration, should predict performance on spatial judgment and memory tasks.

I will test this conjecture with a real-world case study using the campus of Carleton College and a set of undergraduate volunteers. I will perform an axial map analysis of the campus and ask participants to complete a set of spatial judgment and memory tasks. In particular, I hypothesize that:

1. Since the underlying form of spatial knowledge is presumably consistent across people, demographics (the sex and class year of participants) will not affect performance on spatial judgment and memory tasks. Previous research (Dara-Abrams, 2004) indicated no significant differences in performance on any of the tasks to be used in this study between underclass students (six or fewer trimesters on campus) and upperclass students (seven or more trimesters on campus). In addition, other research (German, Kail, and Siegel, 1979) has shown that undergraduate students become familiar with much of their campus within three months (approximately one trimester) if not within three weeks. However, using extreme groups will, it is assumed, conclusively demonstrate that experience is not a confounding factor.
2. Individual differences in spatial ability will affect performance on spatial judgment and memory tasks. In a pilot study (Dara-Abrams, 2004), a self-report questionnaire, the Santa Barbara Sense of Direction Scale (Hegarty, Richardson, Montello, Lovelace, and Subbiah, 2002) was used. Significant correlations were found between scores on that instrument and performance on spatial judgment and memory tasks. However, the creators of that

instrument acknowledge it to be a better measure of ability relevant to real-world wayfinding than to spatial memory and judgment. This study will instead use the Mental Rotation Test (Vandenberg and Kuse, 1978), which has the advantage of being more closely associated with spatial memory and judgment tasks; performance on the test has been found to also measure wayfinding ability (Malinowski, 2001).

3. Systematic distortions, as described by Tversky (1981, 1992), will be observable in participants' responses on spatial judgment and memory tasks.
4. Participants' performance on one spatial judgment and memory task will agree with their performance on another task, as the tasks are designed to make use of the same spatial knowledge.
5. An axial map analysis of the case study environment will produce measures – in particular, measures of global and local integration – that can be compared with results from spatial judgment and memory tasks.
6. These space syntax measures will predict participants' performance on spatial judgment and memory tasks. That is, the integration value associated with particular areas of the case study environment will predict participants' performance when they are asked questions about those areas.

Method

Participants

A total of 32 undergraduate students at Carleton College were recruited to participate in the study. An equal number of first-year and senior-year students were sought, with equal gender balances in each group. All participants were 18 years of age or older and signed informed consent forms (see Appendix) at the beginning of their experiment session. They were compensated for their time with gift certificates.

Instruments

All participants completed four instruments contained in a computer program. Instructions were provided with each instrument. The entire sequence of screens in the program is displayed in Figures 14 – 38. Participants used a Web browser to access the program, which was designed as a Flash movie with Macromedia Flash MX 2004 Professional. The movie files were made available with a Web server running Apache 2 on Windows XP. Also on the server was a script to process data entered by participants into the Flash movie in order to store it in a database running on the server (MySQL 4).

Demographics Questionnaire (DG).

This questionnaire collects basic information on the background of participants: the number of terms that they have been enrolled on campus in Northfield, the location on campus where they have lived, etc. No confidential or private information is collected.

Mental Rotation Test (MRT).

A Mental Rotation Test, MRT, (Vandenberg and Kuse, 1978) is used to assess participants' spatial abilities. After receiving instructions, participants are given three minutes to complete as many of 10 MRT problems as accurately as they can. (See Figure 3 for an example.) Scores are based on the number of problems answered correctly, with possible scores ranging from 0 to 10.

Angle-Measure Task (AMT).

In the Angle Measure Task (AMT), participants are asked to judge and record the relative angle between two buildings, given a pair of well-known buildings on the

Carleton campus, which are drawn from the list of buildings in question (similar to a technique used by Tversky, 1981). All participants are given the same location pairs in the same order. Participants select the desired angle by rotating an arrow around a compass rose until it points in the appropriate direction. The final angle selected is recorded by the software. (See Figure 4 for an example.)

Cutout-Arrangement Task (CAT).

To complete the Cutout-Arrangement Task (CAT), participants are given a blank screen, which has been scaled to the size of the standard campus map, as well as a set of similarly scaled cutouts of the campus buildings on the list of buildings in question. Participants are instructed to place the cutouts in the scaled blank area by dragging and dropping so that the cutouts best approximate the actual orientations and locations of those buildings; participants are allowed to move and rotate the cutouts until they are satisfied with the final arrangement. The software records x- and y-coordinates and rotation for each cutout, so that the arrangement of cutouts can be recreated and so that the angles between buildings can be determined with the use of trigonometric functions.

Procedure

Space Syntax analysis of the campus.

The experimenter began by analyzing the urban configuration of the Carleton campus using space syntax techniques. To prepare for the analysis, the experimenter manually marked axial lines to represent walkways on a CAD (computer-aided design) map of the campus. (AutoDesk AutoCAD 2004 was used for the initial drawing, with touch-up performed in Adobe Illustrator CS.) Axial map analysis was then used on the resulting map using the software package DepthMap (Depthmap; see Turner, 2001, 2004) to determine the global and local integration values of the axes.

Selection of building pairs.

Based on the resulting patterns of deeper and shallower areas of campus, the experimenter selected 12 pairs of buildings with contrasting integration values to use for questions on the AMT (see Figure 5). All of the buildings used on the AMT also appeared as cutouts in the CAT.

Experimental sessions.

All participants began by completing an informed consent form (see Appendix) followed by the DG and then the MRT. The order in which participants received the AMT and the CAT was counterbalanced to remove the potential influence of practice effects. A participant ID was used to identify participants' counterbalance group and to ensure that all of the data collected was properly stored in the database. Upon completion of all four tasks, each participant was compensated, and the experimenter answered any questions the participant had about the experiment.

Data coding.

Performance on the AMT and the CAT is measured by error in degrees. In the case of the AMT, error is simply the difference between a participant's response to an angle-measure question and the true angle. The mean of the error on all 12 questions is considered to represent a participant's performance on the AMT. In the case of the CAT, error is computed to be the difference between the true angle and the angle measured between the pair of building cutouts on a participant's cutout arrangement (computed from the cutouts' x- and y-coordinates with trigonometric functions). The orientation of the building cutouts is not considered.

Results

I will describe this study's results in terms of the six hypotheses previously discussed. All statistical tests used an alpha level of .05.

Demographic Effects

The question is whether participants' performance on the spatial judgment and memory tasks is a property of their particular background or rather an effect of the processes involved in spatial knowledge that are presumably common to all. If the latter is in fact the case, the findings of this study will have broader implications.

As shown by a factorial analysis of variance (ANOVA), participants' mean error on the 12 AMT questions was not significantly affected by their sex or class year. Males' mean error (M = 33.833, SD = 11.263) did not differ significantly from females' (M = 37.224, SD = 18.555) according to the ANOVA, $F(1, 24) = .423$, $p = .521$. First-year students' mean error (M = 37.057, SD = 9.156) did not differ significantly from seniors' (M = 34.000, SD = 19.709) according to the ANOVA, $F(1, 24) = .344$, $p = .563$. Nor did those who took the CAT first (M = 35.537, SD = 17.357) differ significantly from those who took the AMT first (M = 35.521, SD = 13.266) according to the ANOVA, $F(1, 24) = .000$, $p = .998$. However, the test showed a significant interaction between sex and class year, $F(1, 24) = 4.805$, $p = .038$.

No significant demographic effects on performance have been detected, suggesting that all participants are relying on a common form of spatial knowledge.

Individual Differences in Spatial Ability

While demographics do not directly affect performance on spatial judgment and memory tasks, I have suggested that there may be individual differences in spatial ability that do. Do participants' MRT scores actually predict their performance on the tasks?

Note that the MRT score for one female first-year student was thrown out due to improper recording.

MRT score does not predict participants' mean error in degrees on the AMT according to regression analysis, $\beta = -2.153$, $t(30) = -1.633$, $p = .113$. However, MRT score does significantly predict participants' mean error in degrees on the same 12 building pairs on the CAT, $\beta = -4.717$, $t(30) = -3.311$, $p = .002$, and explains a significant proportion of variance in mean error, $R^2 = .274$, $F(1, 30) = 10.964$, $p = .002$.

Thus, the MRT does reveal individual differences in spatial ability on the CAT but not the AMT, suggesting that the two tasks make use of difference processes. I will leave discussion of this possibility for later.

Systematic Distortions

Participants' use of the rotation and alignment heuristics should be apparent in systematic distortions in their responses on the AMT and CAT.

The correct angles for the 12 AMT questions are displayed in Figure 5, with the arrows pointing from the starting location to the given destination. In Figure 6, these angles have been rotated by the mean error in degrees aggregated among all participants (shown in blue). That is, the blue angles stand for the average response by participants. For example, participants incorrectly place West Gym to the northwest of Musser Hall. This may be due to the fact that West Gym is on the west side of Highway 19 and Musser Hall is on the east side – if the highway is orthogonalized to north-south, in keeping with Tversky's rotation heuristic, participants will be led to the incorrect northwest response, since West Gym is shifted to the west as the highway is rotated counterclockwise.

Such systematic distortions are more apparent in participants' responses on the CAT. For example, Figure 13 shows one participant's arrangement of the cutout pieces, which is representative of many of the responses. Note the use of the rotation and alignment heuristics – the buildings have been arranged in orthogonal lines.

The prevalence of these systematic distortions appears to confirm the use of the rotation and alignment heuristics by the participants when completing the spatial judgment and memory tasks.

Agreement Between Instruments

If the AMT and the CAT ask participants to make use of the same spatial judgment and memory processes, one's performance on the AMT should correlate highly with one's performance on the CAT. Mean error in degrees on the 12 AMT questions significantly correlates with mean error for the same building pairs on the CAT, $r(30) = .492$, $p = .004$, supporting the conclusion that the tasks are fundamentally similar. This finding is in contrast to the regression analysis showing that MRT score predicts performance on the CAT but not the AMT.

Space Syntax Analysis of the Campus

Space syntax measures of the test environment are needed to compare with the results from the spatial judgment and memory tasks. Figure 7 shows the axial map of the Carleton campus generated by the experimenter. The weight of each line represents the global integration of that axis – the thicker the line, the higher the global integration value. Local integration, with radius three, is similarly displayed in Figure 8. Each axis represents a straight line down a walkway. The axial maps can be compared to the campus map in Figure 5 to see the relative location of the various buildings.

Agreement Between Instruments and Space Syntax Analysis

Do these integration values from the space syntax analysis predict performance on the spatial judgment and memory tasks? In particular, I will consider the integration value of the axis leading to the main entrance of each building. When two or more axes converge at an entrance, I will use the higher integration value. Thus, performance on the AMT can be compared against the integration values of the starting and ending buildings for each question, and similarly for any pair of buildings on the CAT.

Mean error in degrees (aggregated among all participants) for each AMT question is significantly predicted by the global integration of the first of the pair of buildings (the given building as opposed to the destination building), $\beta = -13.855$, $t(10) = -2.435$, $p = .035$, and accounts for a significant proportion of variance in mean error, $R^2 = .372$, $F(1, 11) = 5.930$, $p = .035$. See Figure 9. However, the global integration value of the destination building does not significantly predict the aggregate mean error in degrees, $\beta = 2.609$, $t(10) = 1.936$, $p = .710$. Put more simply, the global integration value of the starting building predicts participants' performance on a given AMT question, but the global integration value of the destination building does not have similar predictive power.

Local integration of the starting building does not significantly predict the aggregate mean error in degrees, $\beta = -2.407$, $t(10) = 2.180$, $p = .531$, suggesting that only global integration values have bearing on spatial judgment and memory tasks, and thus on our spatial knowledge.

Let us leave that broader theoretical question to the side for the moment and consider how well global integration values predict performance on the CAT.

The global integration value of the starting building significantly predicts the mean error in degrees on the angles between the same 12 building pairs as they were arranged in the CAT, β = -12.046, *t*(10) = -2.718, *p* = .022, and accounts for a significant proportion of variance in mean error, R^2 = .425, *F*(1, 11) = 7.386, *p* = .022. See Figure 10. Again, mean error is not significantly predicted by the global integration value of the destination building, β = -1.301, *t*(10) = -.233, *p* = .820. In other words, the global integration value of the starting building again predicts participants' performance on the CAT, at least with respect to the 12 building pairs considered in the AMT questions.

To test whether this property is limited to those 12 buildings pairs, I considered another set of 12 building pairs, shown in Figure 11. On this new set of building pairs, the global integration value of the starting building does not significantly predict the mean error in degrees of the angle between the two buildings, β = -2.393, *t*(10) = -.535, *p* = .604. See Figure 12.

Particularly for the 12 original building pairs considered, the global integration value associated with the starting building's entrance significantly predicts participants' error in determining the angle from that location to another building. This is true whether participants are considering that angle in the AMT by rotating the pointer ball or in the CAT by placing cutout pieces. The higher the starting building's global integration value, the smaller the mean error made by participants. However, global integration values do not appear to make similarly significant predictions on all possible building pair combinations on the CAT.

Discussion

Are the Same Processes at Work?

Are the same processes at work when a person makes angle judgments in the AMT as when they choose where to place cutout pieces in the CAT? Each participant's performance on the AMT correlated highly (r = .492) with their performance on the CAT. Yet participants' MRT scores only predicted their performance on the CAT but not on the AMT. These results appear at odds with one another, the first finding suggesting a strong connection between the instruments, while the second suggesting that only the CAT relies closely on mental rotation. First, it must be noted that the correlation between the instruments is not large enough to control all variation in performance – these two findings may not be in disagreement.

My previous work (Dara-Abrams, 2004) suggests that the two instruments are actually different in nature. In that study, participants completed the Santa Barbara Sense of Direction Scale (Hegarty et al., 2002), which asks them to rate their confidence and ability at reading maps and navigating real-world environments. Participants' scores on that questionnaire correlated highly (r = -0.54) with their AMT performance but not their CAT performance. Apparently AMT performance is more closely connected with one's real-world wayfinding abilities, while CAT performance is more directly associated with one's mental rotation abilities.

Consider the differences between the AMT and the CAT. On the AMT, participants must imagine where the destination building stands in relation to the pointing dot, much as while navigating through an environment, we must imagine where our out-of-sight destination lies. On the CAT, participants can see all the buildings on campus as they move one around the screen, much as how we evaluate one object rotating in relate to its surroundings. These are abilities measured by the Santa Barbara Sense of Direction Scale and the AMT, respectively. Thus, the findings of this study demonstrate that wayfinding abilities and mental rotation abilities are intimately connected – performance on the two tasks is highly correlated – but that these abilities are best measured by two different tests.

The Form of Spatial Knowledge

Whether or not the CAT and the AMT make use of the same set of processes, they both call on the same set of spatial knowledge. Tversky (1981, 1992) has already demonstrated that this spatial knowledge is shaped by the alignment and rotation heuristics, and this study's findings only support that conclusion. What this study can contribute is evidence of how that systematically distorted spatial knowledge is shaped by the configuration of the environment in question.

It is the integration value associated with the starting building that predicts participants' performance on the spatial judgment and memory tasks, suggesting that participants' spatial knowledge of the place in which they are asked to imagine themselves is the key determiner of their performance. The format of the AMT, with the simple line drawings from a bird's-eye view of the starting location, certainly suggests that they must use their prior spatial knowledge to associate that abstraction with an actual location. On the other hand, participants' spatial knowledge of the place they are asked to imagine pointing toward does not significantly affect their performance. This evidence implies that people only consider the local properties of the starting building when making such judgments.

However, recall that global integration but not local integration is strongly predictive. Since global integration measures interconnectedness with the entire axial map, the global integration value associated with the starting building will take into account the entire configuration of the test environment. Correspondingly, people may be considering the entire test environment when performing spatial judgment and memory tasks. While people may be consciously considering the global form of the environment in order to determine their responses, this evidence suggests that their spatial knowledge itself may be global in form. People's spatial knowledge may be structured as a comprehensive unit as opposed to being structured as a set of discrete, localized chunks.

This Particular Case Study

Properties of the particular test environment used have certainly shaped the findings of this study, including the implication that spatial knowledge may be global in form. The Carleton campus is a well-defined area with definite boundaries, although sides of the campus do abut residential neighborhoods and the downtown. Would a different test environment produce similar results? If so, we may want to conclude that spatial knowledge is stored and used in a global form. Based alone on the findings in this study, I am led to propose instead that the participants' spatial knowledge of the Carleton campus is global in form in reflection of the fact that the campus can stand as a discrete spatial region in memory. In other words, the urban form of the environment is shaping the form of people's spatial knowledge.

One unfortunate property of using the Carleton campus as a case study is that most of the building pairs that appear to be affected by systematic distortions include one building in the central (orthogonal) area of campus (e.g., the Language and Dining Center) and one building on the periphery of the campus (e.g., the Recreation Center), where the buildings are oddly-angled and are not arranged orthogonally. Those buildings that are on the periphery will most likely have lower global integration values. Is this due to the fact that they are on the periphery, and thus less centrally located, or are the low global integration values instead an effect of those buildings' odd angles and non-orthogonal arrangement? The Carleton campus offers few clear examples for considering this question. A natural continuation of this study would be to consider other test environments that include more instances of significant systematic distortions.

Also of concern is the accuracy of the axial map. The axial map used in this study limits the sightlines to pathways. Yet people clearly traverse other routes as they move around the campus. Moreover, they can see across open quadrangles, lawns, and roadways, none of which are considered with this axial map. A redrawn axial map that considers all spaces accessible to pedestrians (in ideal weather, presumably) might lead to different integration values for buildings. For example, redrawing the axes to allow for people walking across the Bald Spot (see Figure 5) would restructure the routes among all of the buildings fronting that region, and by extension, the global integration values for all buildings would be affected.

Although new and unproven algorithms exist for automatically generating axial maps, the axes are almost always drawn out by hand, which may lead to variance between axial maps drawn by different experimenters. For instance, the question of whether to draw a separate axis leading to a building's front door is quite subjective. The axial map used for this study may not be as precise or as accurate as it could be – more reason to repeat this study with different test environments.

Axial map techniques were originally designed for analyzing dense urban areas with well-defined streets edged by solid lines of buildings. Obviously the Carleton campus, with its loose spacing of buildings and open quadrangles is quite different in its form. Newer space syntax techniques, especially those designed for measuring visibility in open areas of building interiors, may be better suited for analyzing spaces like the Carleton campus.

Regardless, this study does demonstrate that a real-world case study both supports Tversky's theory of the alignment and rotation heuristics and provides evidence of how urban form shapes spatial knowledge. Unlike in Tversky's (1981) studies, these spatial judgment and memory tasks asked participants to use spatial knowledge learned primarily through direct contact – taking tours of the campus and walking around on their own – rather than through maps and other visual displays. While this study was performed in a laboratory setting, its use of real-world knowledge can be said to lend some ecological validity to these findings.

A Connection Between Cognitive Science and Urban Design

This study bridges two very distinct disciplinary worlds, that of cognitive science and cognitive psychology on the one hand and of architecture and urban design on the other. Whereas the former is concerned with producing a theoretical and empirical account of the human mind and similar agents, the latter focuses on the design and analysis of physical places. With this study I have attempted to empirically connect the two areas of research. With respect to cognitive science and cognitive psychology, these results provide real-world evidence of the rotation and alignment heuristics, while suggesting how our spatial knowledge relates to the urban form of an environment. At the same time, the results of this study lend support to the tools of space syntax, implying that they accurately describe properties of environments that we encode into our spatial knowledge. Thus, these tools have psychological meaning and can assess the human use and knowledge of environments. In architecture and urban design, fields in which aesthetics are all too often the only consideration, space syntax measures could provide a useful method for also taking into account how humans actually perceive and use their surroundings. The gulf between the world of cognitive science and cognitive psychology and the world of architecture and urban design may not be as wide as conventionally assumed.

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Figure Captions

Figure 1. In this bird's-eye view map, axes (black lines) represent sightlines bounded by the gray areas, which cannot be traversed or seen through. Each of the eight axes is numbered (bold type) and its integration values are given (light type) with global integration given before local integration. One number is listed in cases where the global integration of a node is equal to the local integration.

Figure 2. This graph shows the connections between the axes from Figure 1, labeled by the same numbers. The metric information such as the length of each axis has been discarded, while the topology of the axes is retained.

Figure 3. An example of a problem from the Mental Rotation Test (Vandenberg and Kuse, 1978). Participants are presented with a block figure with a particular orientation (far left) as well as four other illustrations of block figures. Two of these block figures have the same structure as the given block figure but have been rotated—the task is to identify and mark these. The other two block figures have different structures. The correct answers have been marked on this example.

Figure 4. An example of a problem from the Angle-Measure Task (above). Participants are instructed to draw an arrow through the compass rose pointing from the given location to the given destination. In this example, an arrow has been drawn with the correct angle. This can be confirmed by checking the extract from a campus map (below).

Figure 5. The 12 building pairs used for the AMT. Arrows point from the given (first) building toward the destination building.

Figure 6. True angles for the 12 AMT questions are given in red (as in Figure 5). Blue arrows are adjusted to reflect the mean error made by participants. Note the systematic

distortions, particularly the movement of West Gym, Goodhue Hall, and the Recreation Center.

Figure 7. On this map, axes represent pathways on the Carleton campus. Thicker lines indicate higher global integration values.

Figure 8. Thicker lines on this axial map, which uses the same axes as Figure 7, indicate higher local integration values (integration computed within a radius of three nodes).

Figure 9. The global integration value of the start building plotted against mean error in degrees on the 12 AMT questions.

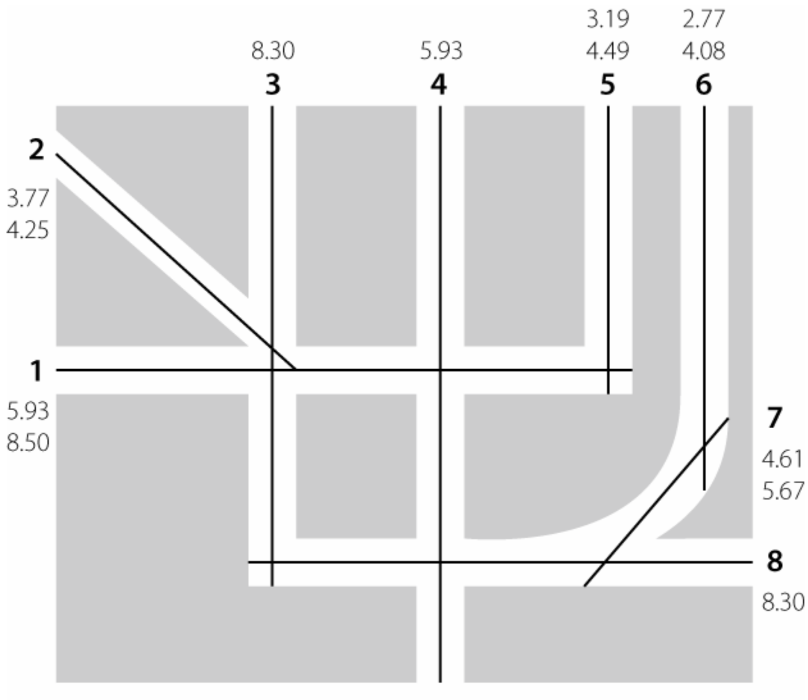
Figure 10. The global integration value of the start building plotted against mean error in degrees on the 12 AMT building pairs, with angles drawn from participants' arrangements on the CAT.

Figure 11. A second set of 12 building pairs drawn from the CAT. Note that this set appears to include fewer building pairs that would clearly be affected by systematic distortions than the original set of 12.

Figure 12. The global integration value of the start building plotted against mean error in degrees on the 12 new building pairs, with angles drawn from participants' arrangements on the CAT.

Figure 13. One participant's response on the CAT. Note the use of the rotation and alignment heuristics—the buildings have been arranged in orthogonal lines.

Figures 14 – 38. Participants advanced through this series of screens to complete the computer-based experiment program. In this example, the participant completes the AMT before the CAT. Half of the participants received the tasks in this order, and the other half received the reverse.



3.19
4.49
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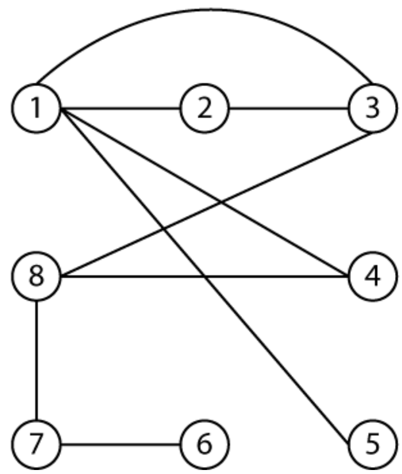
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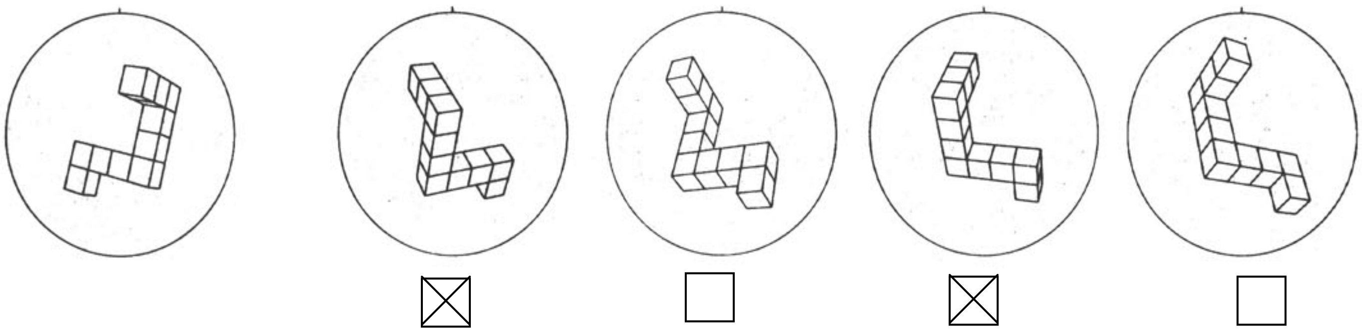
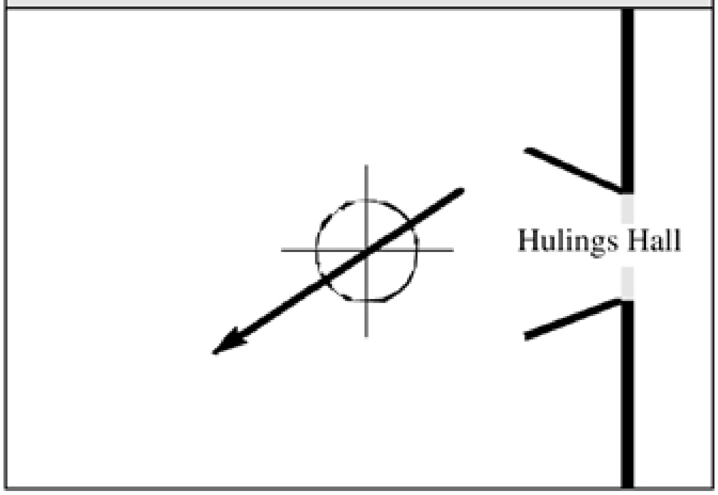
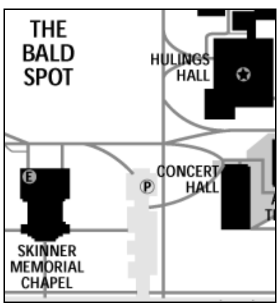
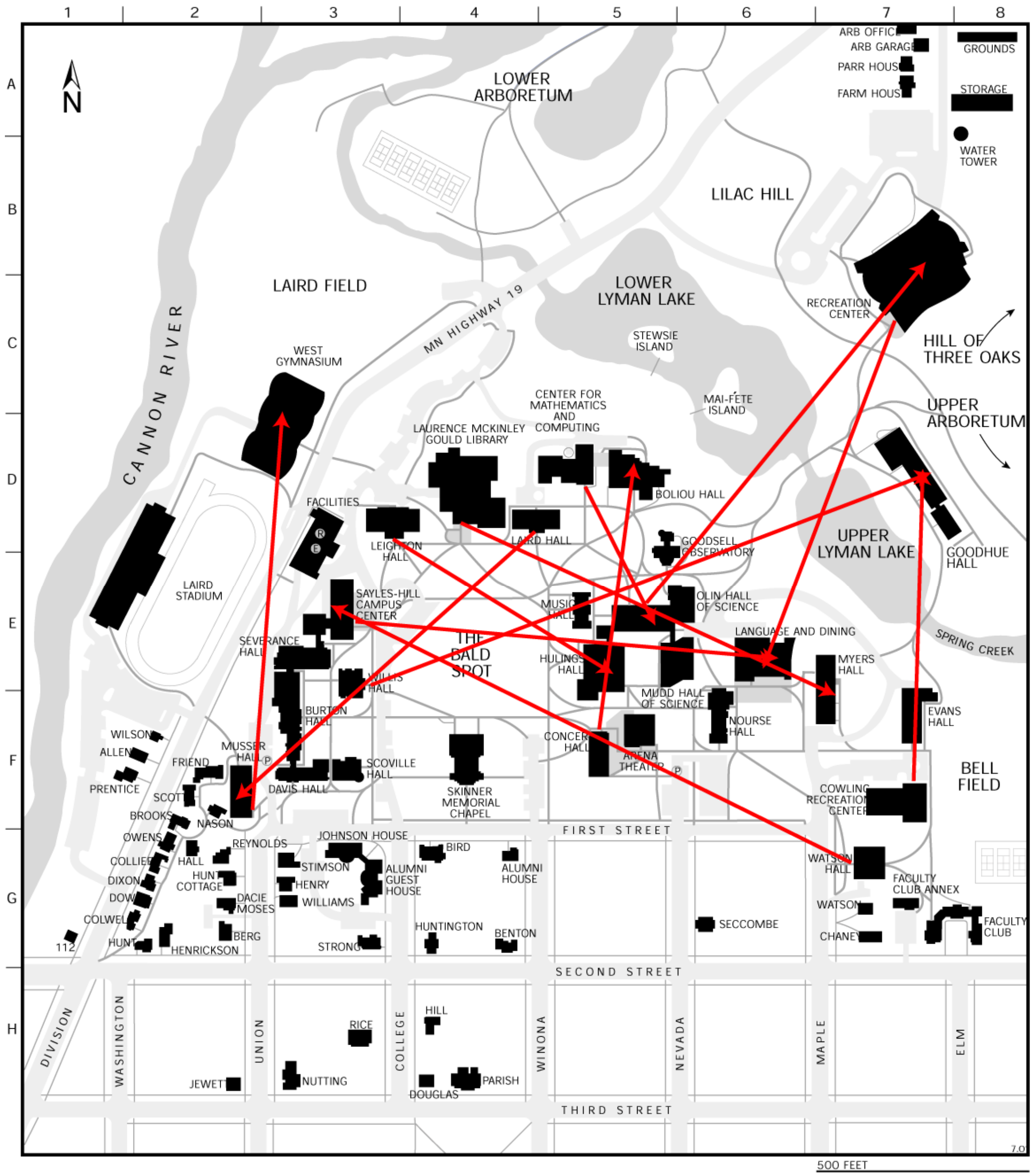


Present location:	**front door to Hulings Hall**
Destination:	**Skinner Memorial Chapel**







LOWER ARBORETUM
LILAC HILL
LAIRD FIELD
LOWER LYMAN LAKE
STEWSIE ISLAND
MAI-FETE ISLAND
MN HIGHWAY 19
CANNON RIVER
WEST GYMNASIUM
RECREATION CENTER
HILL OF THREE OAKS
UPPER ARBORETUM
CENTER FOR MATHEMATICS AND COMPUTING
LAURENCE MCKINLEY GOULD LIBRARY
BOLIOU HALL
FACILITIES
LEIGHTON HALL
LAIRD HALL
GOODSELL OBSERVATORY
UPPER LYMAN LAKE
GOODHUE HALL
LAIRD STADIUM
SAYLES-HILL CAMPUS CENTER
MUSIC HALL
OLIN HALL OF SCIENCE
SEVERANCE HALL
THE BALD SPOT
HULINGS HALL
LANGUAGE AND DINING
MYERS HALL
SPRING CREEK
WILLIS HALL
BURTON HALL
MUDD HALL OF SCIENCE
NOURSE HALL
EVANS HALL
WILSON
ALLEN
PRENTICE
FRIEND
MUSSER HALL
SCOTT
BROOKS
NASON
OWENS
DAVIS HALL
SCOVILLE HALL
SKINNER MEMORIAL CHAPEL
CONCERT HALL
ARENA THEATER
BELL FIELD
COWLING RECREATION CENTER
FIRST STREET
REYNOLDS
JOHNSON HOUSE
BIRD
COLLIER
HALL
HUNT COTTAGE
DIXON
DOW
COLWELL
HUNT
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STIMSON
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WILLIAMS
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HENRICKSON
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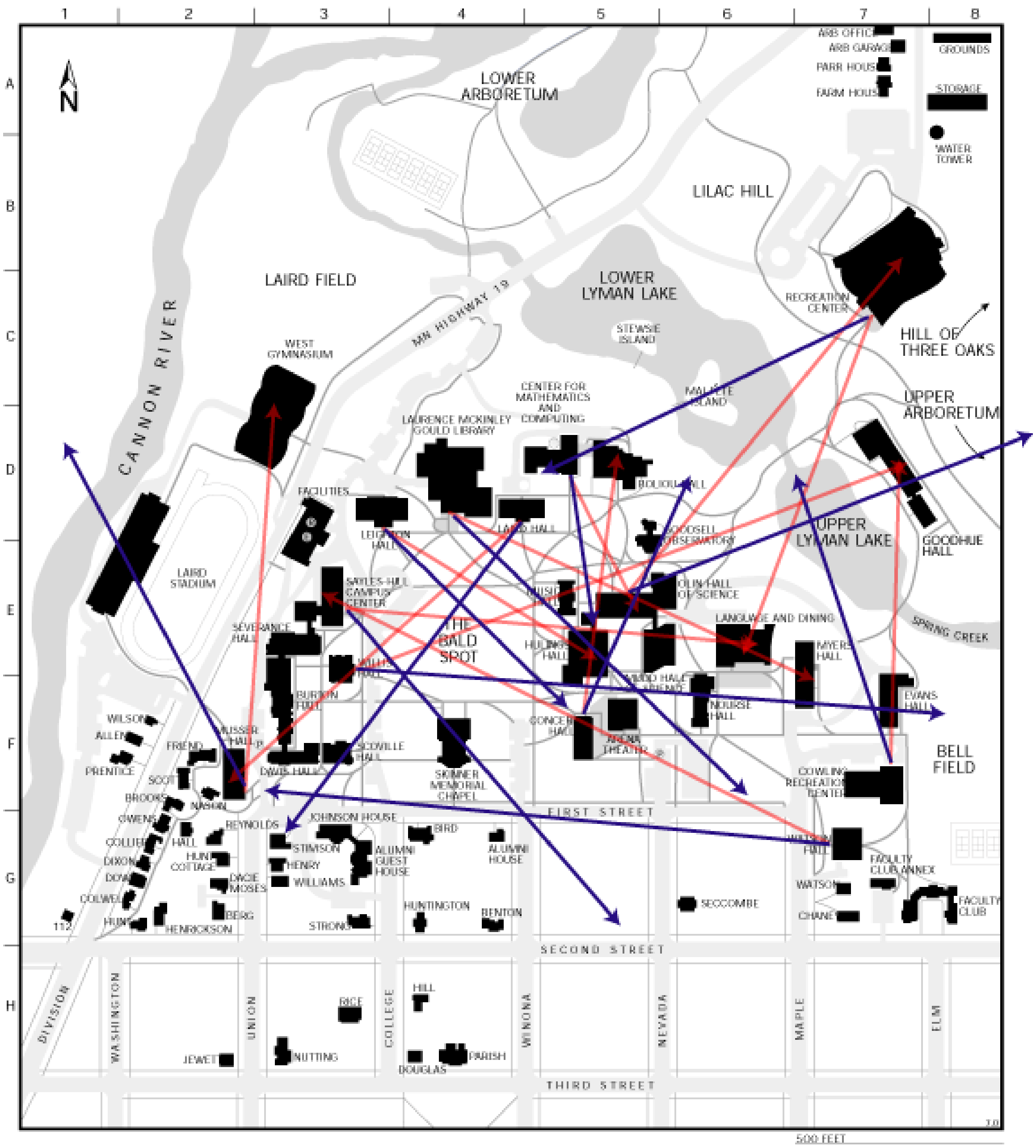
GROUNDS
STORAGE
WATER TOWER
500 FEET



LOWER ARBORETUM
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MN HIGHWAY 19
WEST GYMNASIUM
RECREATION CENTER
HILL OF THREE OAKS
UPPER ARBORETUM
UPPER LYMAN LAKE
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LANGUAGE AND DINING
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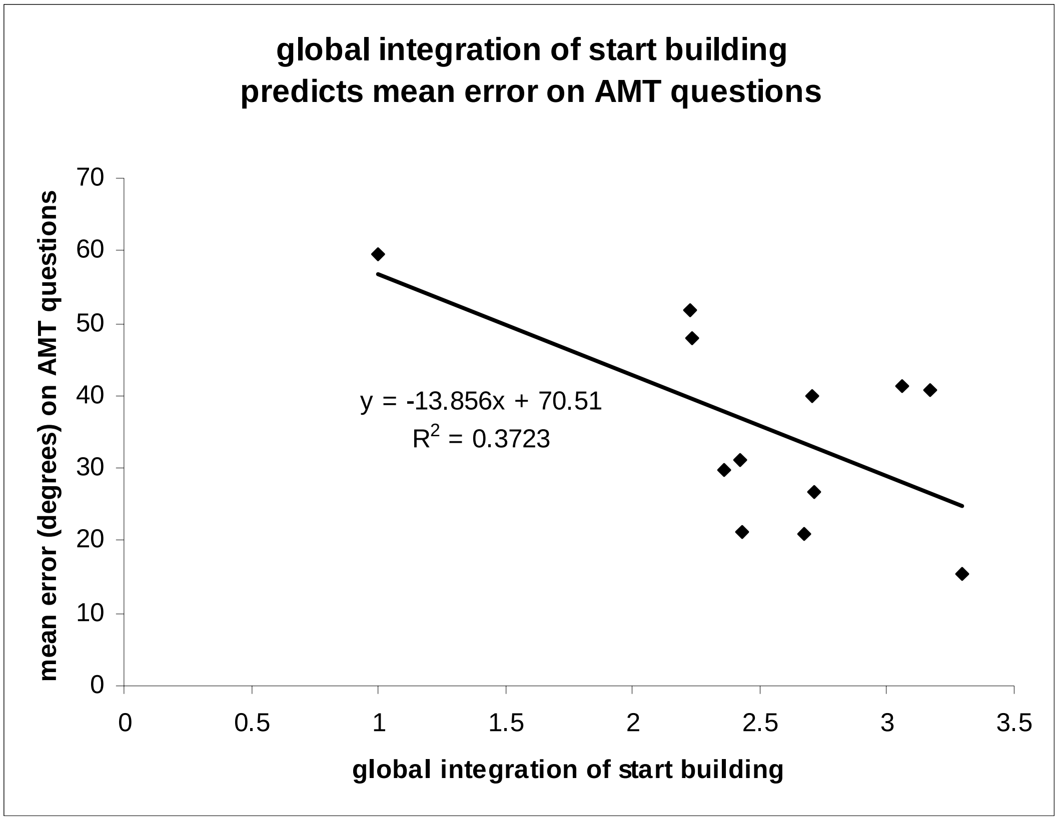
global integration of start building
predicts mean error on AMT questions
mean error (degrees) on AMT questions
y = -13.856x + 70.51
R2 = 0.3723
0
10
20
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40
50
60
70
0
0.5
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1.5
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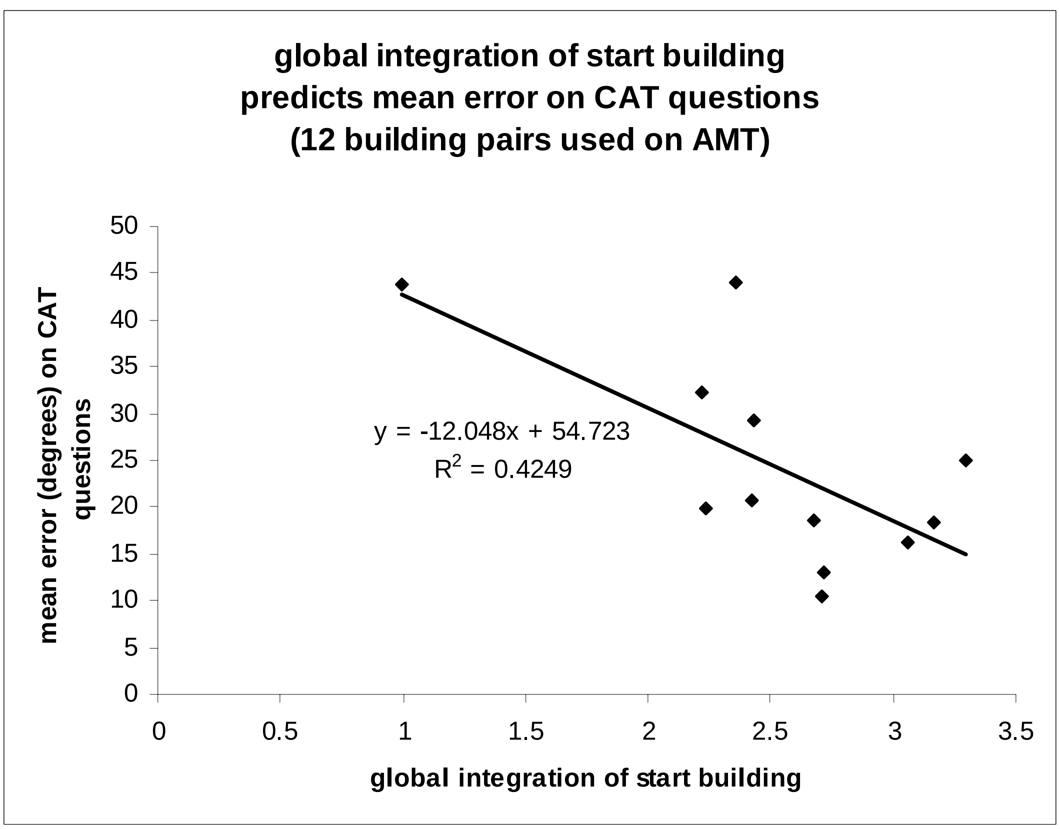
2.5
3
3.5
global integration of start building


global integration of start building
predicts mean error on CAT questions
(12 building pairs used on AMT)
mean error (degrees) on CAT questions
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R2 = 0.4249
0
5
10
15
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0.5
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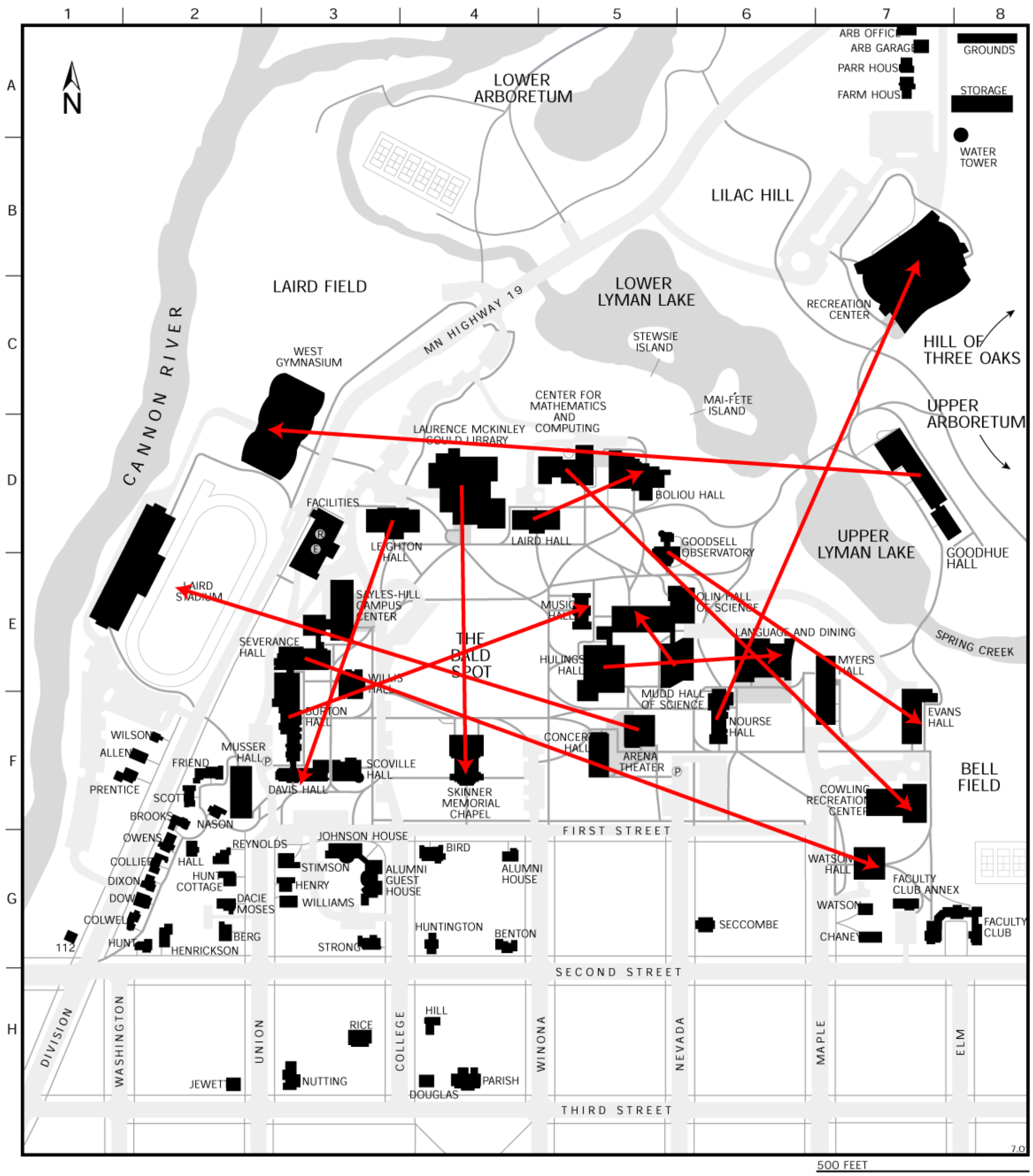
3
3.5
global integration of start building



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ALUMNI GUEST HOUSE
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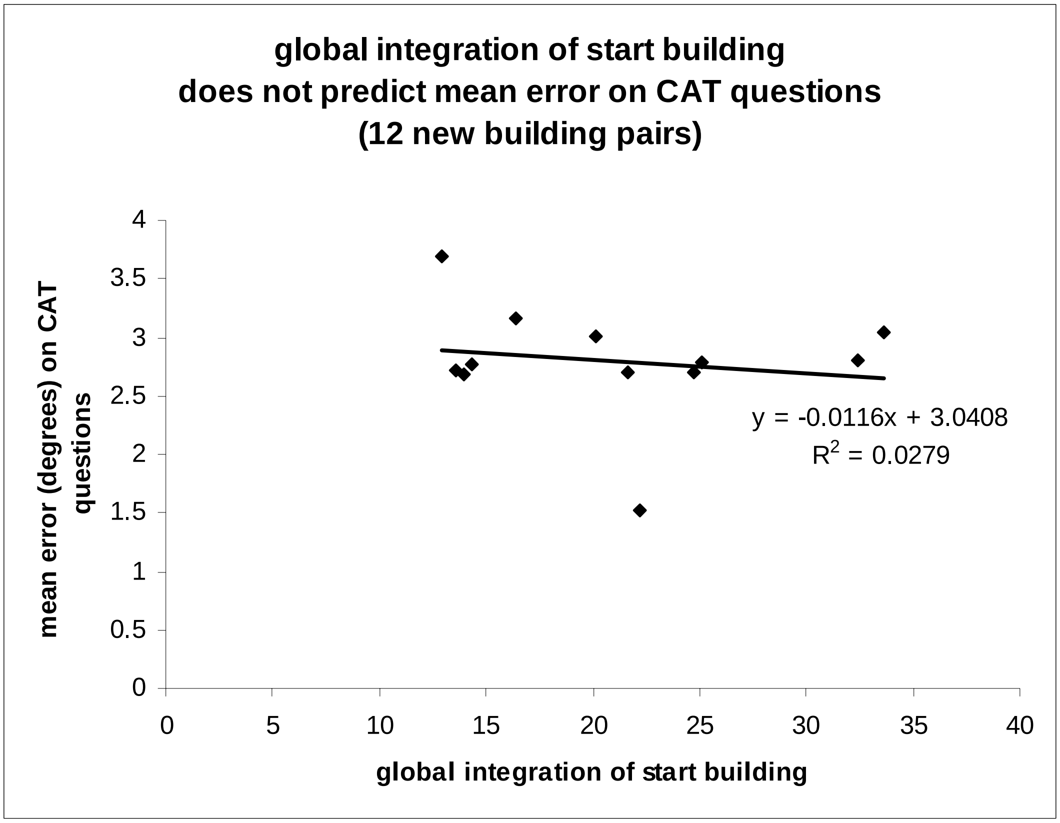
global integration of start building
does not predict mean error on CAT questions
(12 new building pairs)
mean error (degrees) on CAT questions
global integration of start building
y = -0.0116x + 3.0408
R^2 = 0.0279
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
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25
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35
40

Spatial Tasks

Version 1.1 / February 2005
by Drew Dara-Abrams

Please begin by reviewing the informed consent form, signing to indicate that you agree to participate in the study. The participant ID indicated in the upper right corner of the page is the only piece of identifying information that will be attached to your responses to these computer-based questionnaires. Please enter your participant ID number below.

Participant ID

[ ]

Continue

Demographics Questionnaire

For how many trimesters have you been enrolled on campus at Carleton (including this term)? Count summers as a trimester.

[ ] trimesters

Your gender?

Male ▾

During your time on campus at Carleton, for how many trimesters have you lived in each of the following locations?

[ ] west-side dorm/townhouse

[ ] east-side dorm

[ ] neighborhood (off-campus) house

[ ] downtown

[ ] other

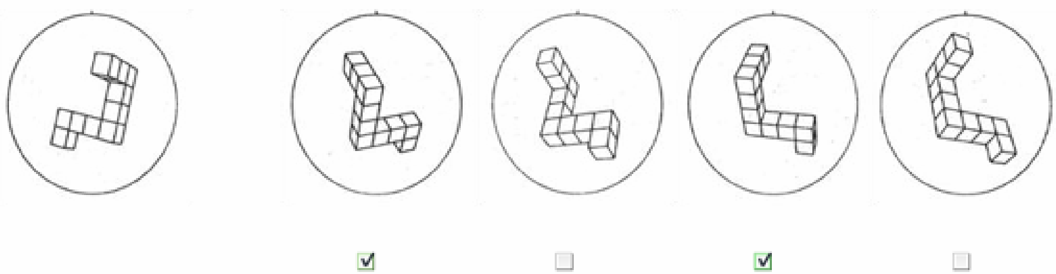
Continue

Mental Rotation Test

This part of the study is a measure of your spatial abilities. You will be presented with 10 questions along the lines of the following example. Each question consists of a sample geometric figure (on the left) with a particular orientation, along with 4 other figures (on the right), 2 of which are identical to the sample figure but rotated slightly—if you rotate these 2 figures, they will match the sample figure. The other two figures will never match the sample, no matter how much you rotate them. Your task is to identify and mark the 2 figures that match the sample figure. Only select 2 of the figures. You will be given 3 minutes to complete as many of the problems as you can.

The correct answer choices have been selected in this example question. If you have any questions, please ask the experimenter at this time.

Example Question



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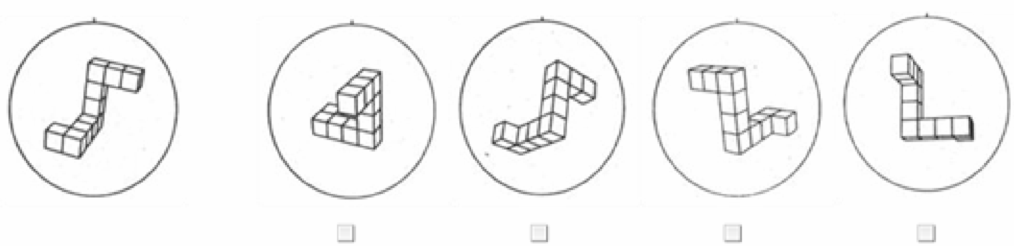

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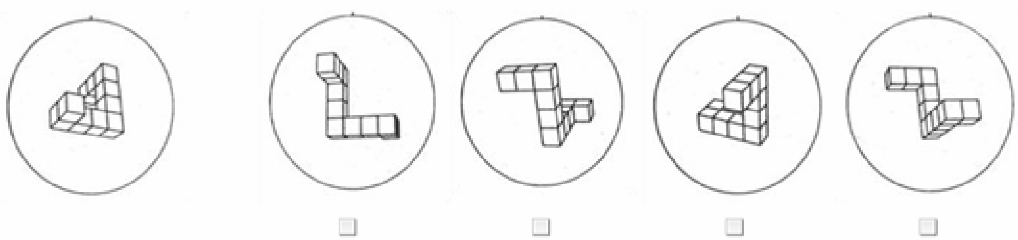

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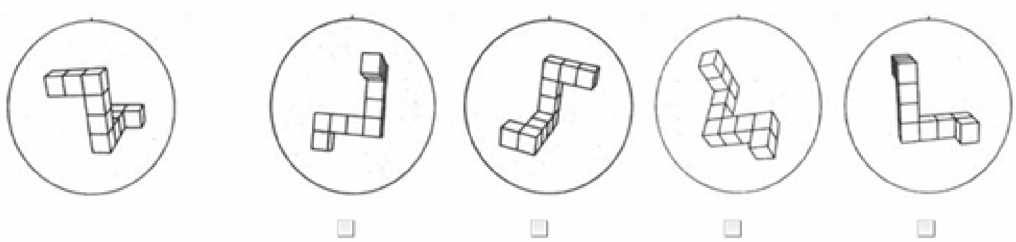

Continue to the Next Questions

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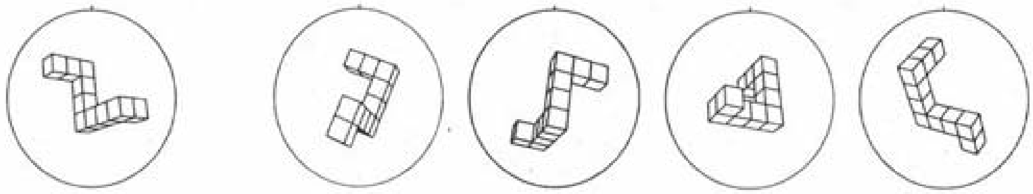

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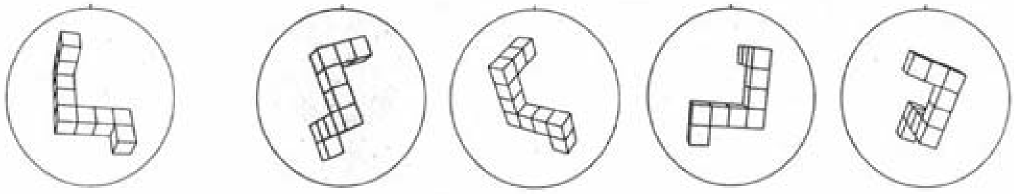

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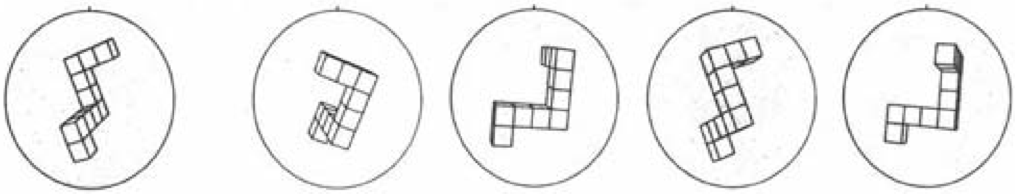

Continue to the Next Questions

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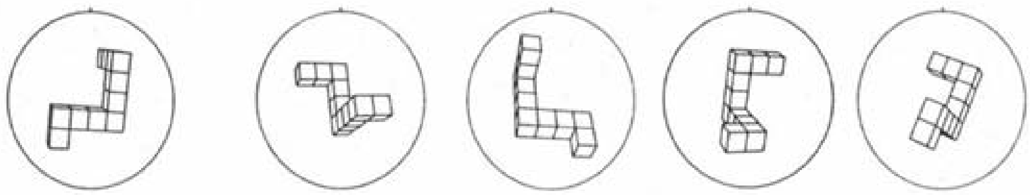

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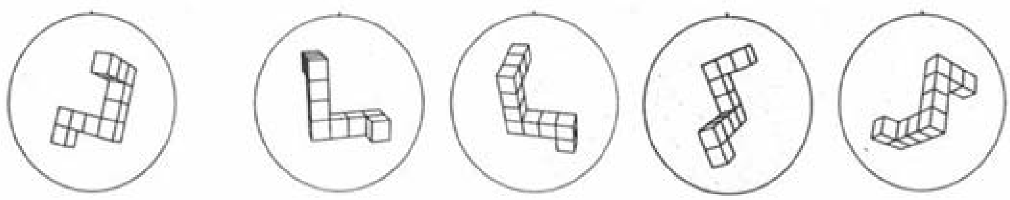

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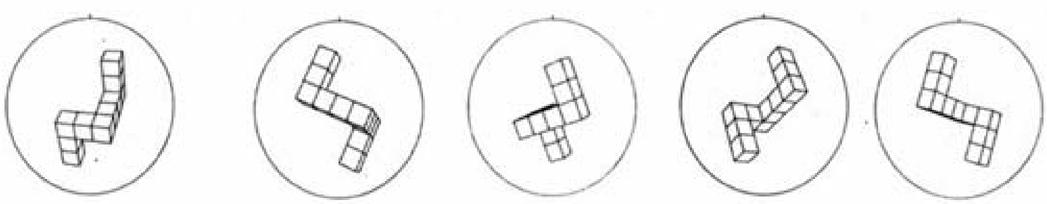
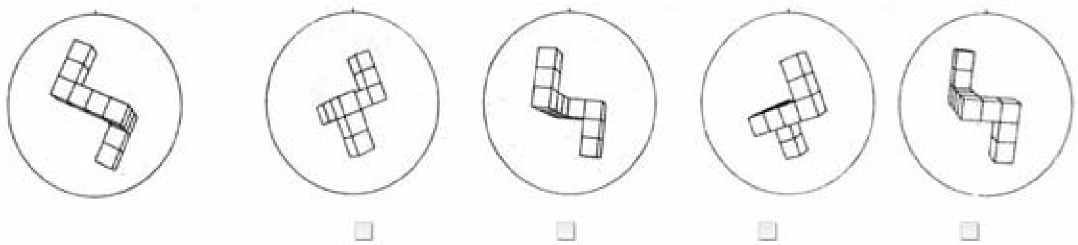


Continue to the Final Question

10 

I am Finished

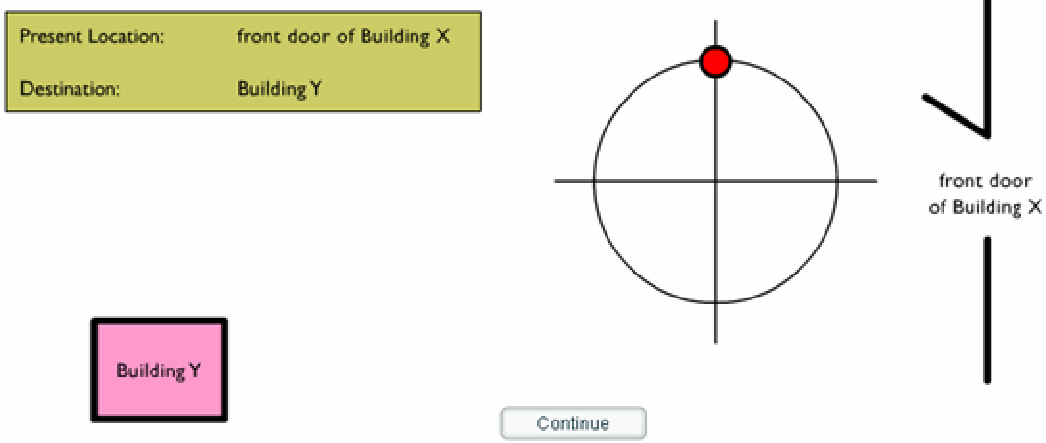
You have completed the Mental Rotation Test.

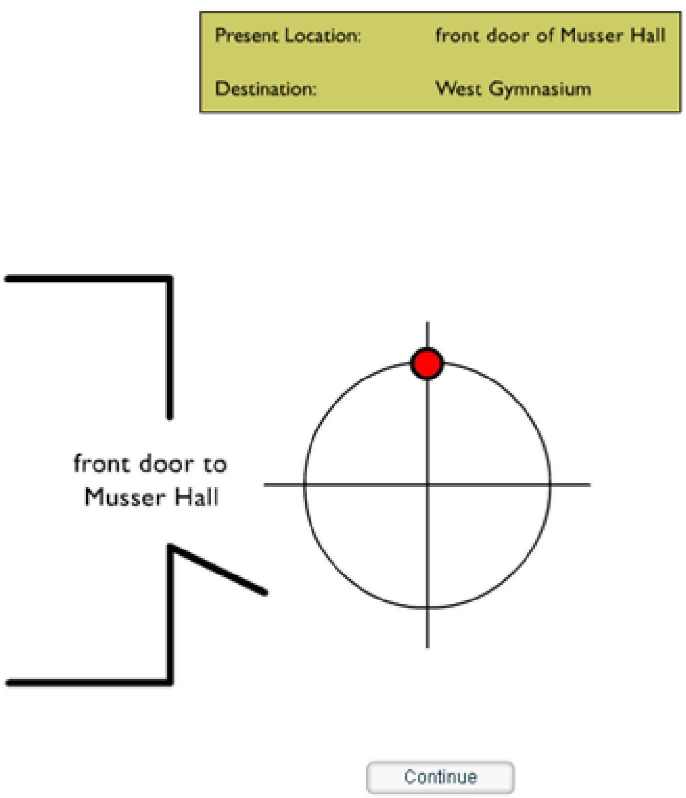
Continue

Angle-Measure Task

In each of the following 12 questions, you will be asked to assume that you are standing at a well-known point on the Carleton campus and that a passerby is asking you for directions to another well-known point on campus. This passerby, for whatever reason, can travel through walls, buildings, trees, and any other potential obstacles as well as travel over water. Therefore, she only asks that you point in the direction of the destination. Please indicate the exact direction in which you would point by dragging the red dot to the correct angle, on the diagram as shown in the example below. The center of the crosshairs represents the location from which you are pointing. Note that the drawings, such as the example below, are bird's eye views of your present location. You can try rotating the ball to point toward the destination in the following example. In the real questions you will not see the destination on the screen. Please ask the experimenter any questions you may have.

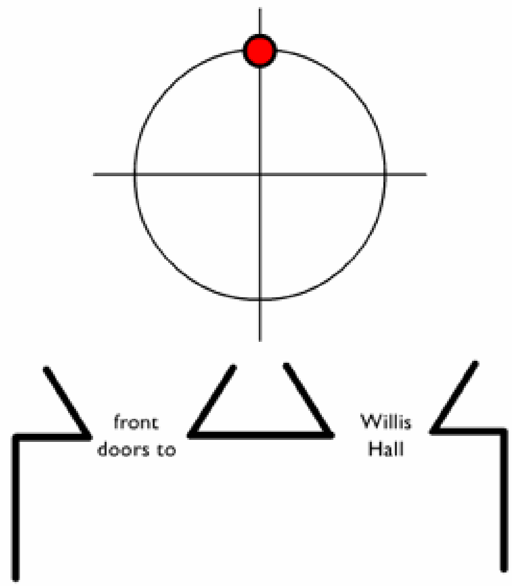
Example Question





Present Location: sidewalk in front of Willis Hall

Destination: Goodhue Hall



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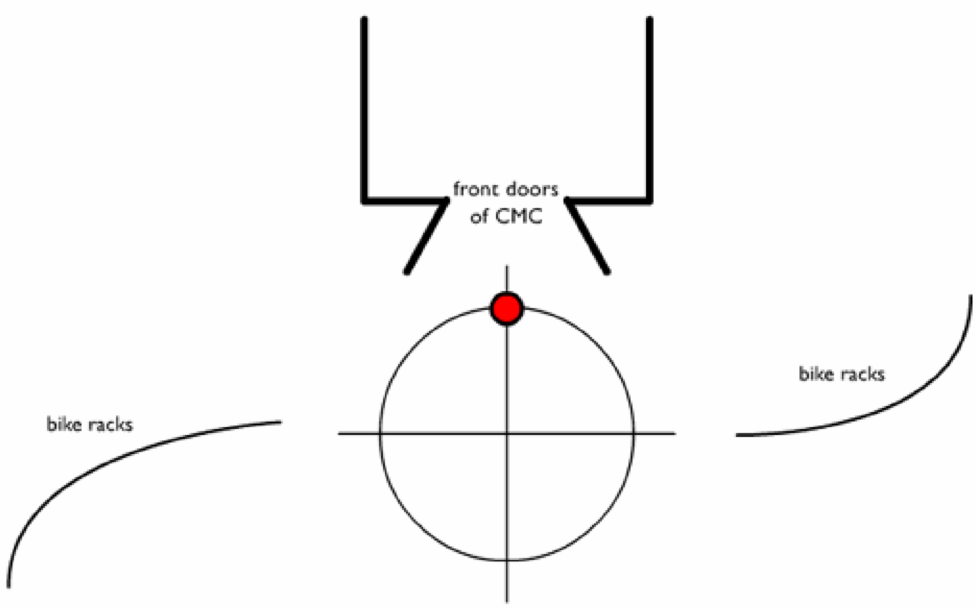
Present Location: front doors of CMC

Destination: Olin Hall



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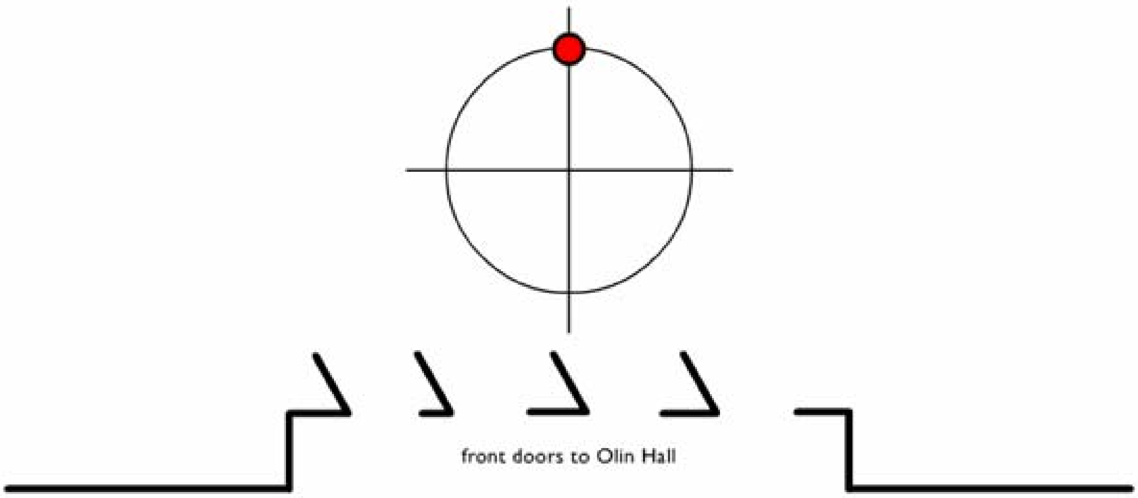
Present Location:	front doors of Olin Hall
Destination:	Recreation Center



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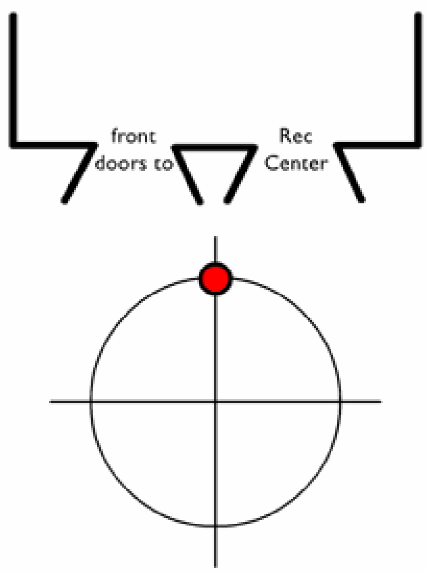
Present Location:	front doors of Recreation Center
Destination:	Language and Dining Center



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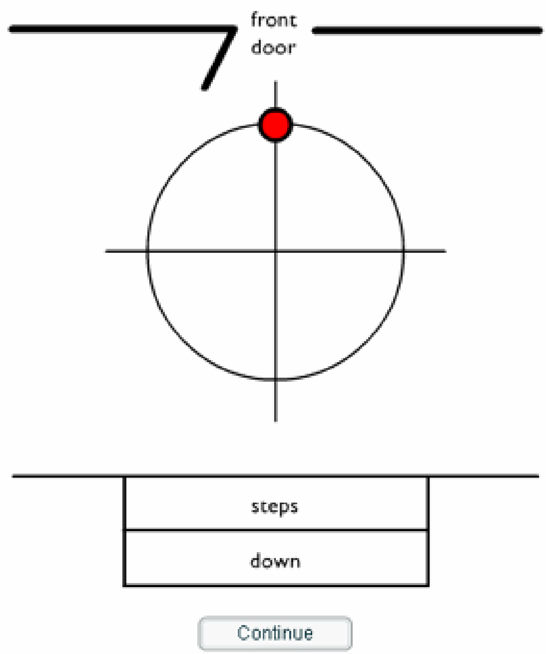
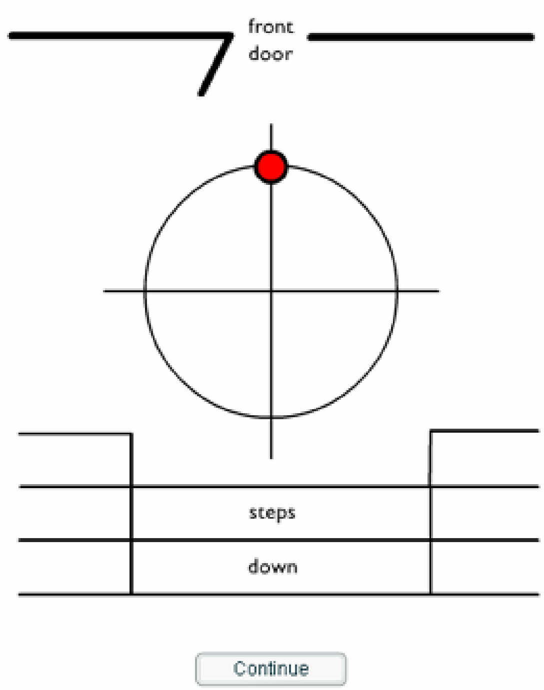
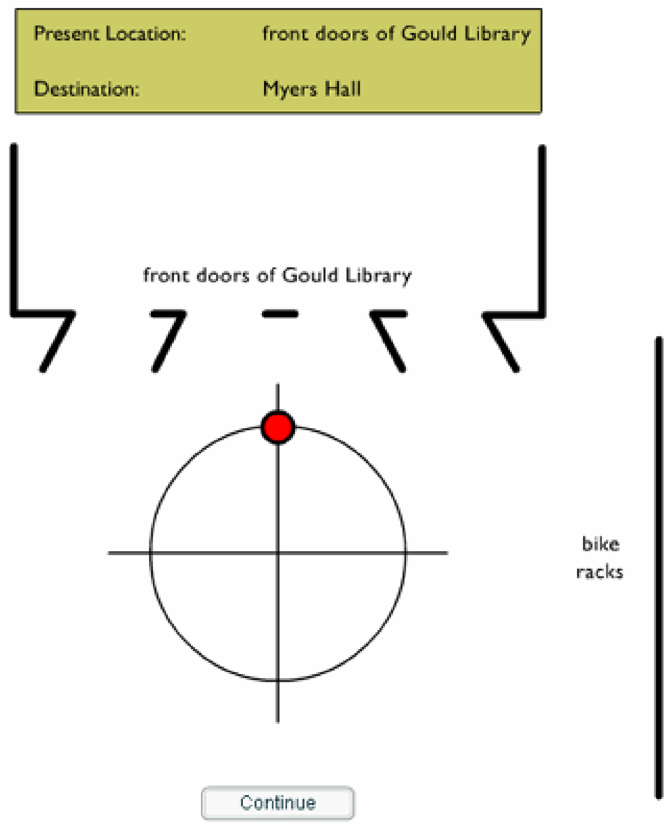
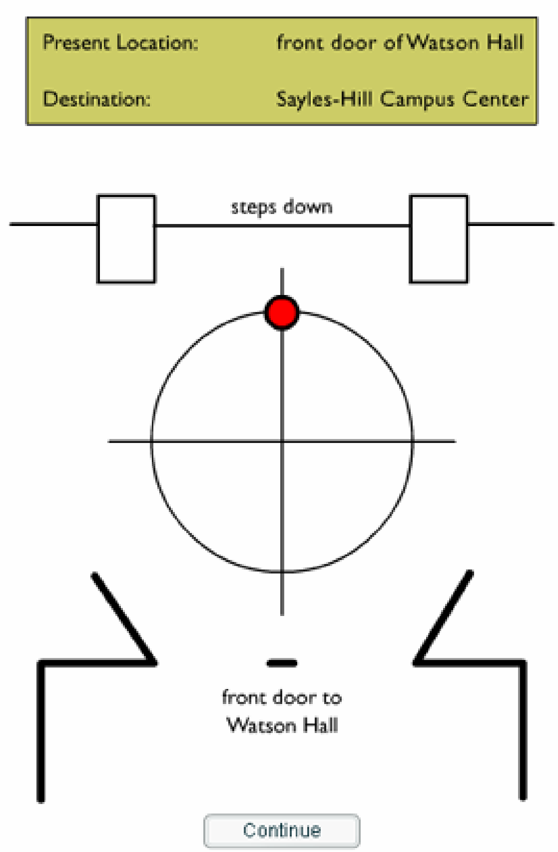
Present Location:	front door of Cowling Recreation Center
Destination:	Goodhue Hall



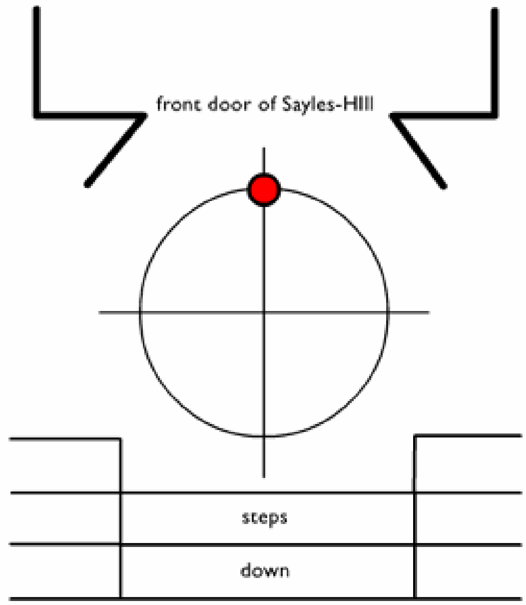
Present Location:	front door of Laird Hall
Destination:	Musser Hall




Present Location: front doors of Gould Library
Destination: Myers Hall
front doors of Gould Library
bike racks
Continue

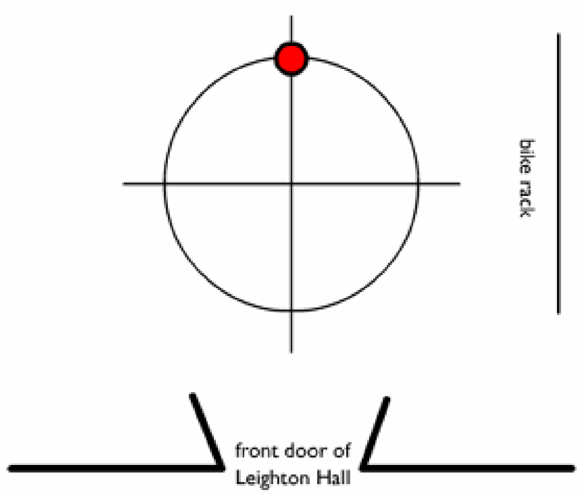

Present Location: front door of Watson Hall
Destination: Sayles-Hill Campus Center
steps down
front door to Watson Hall
Continue

Present Location:	front door of Sayles-Hill Campus Center
Destination:	Language and Dining Center

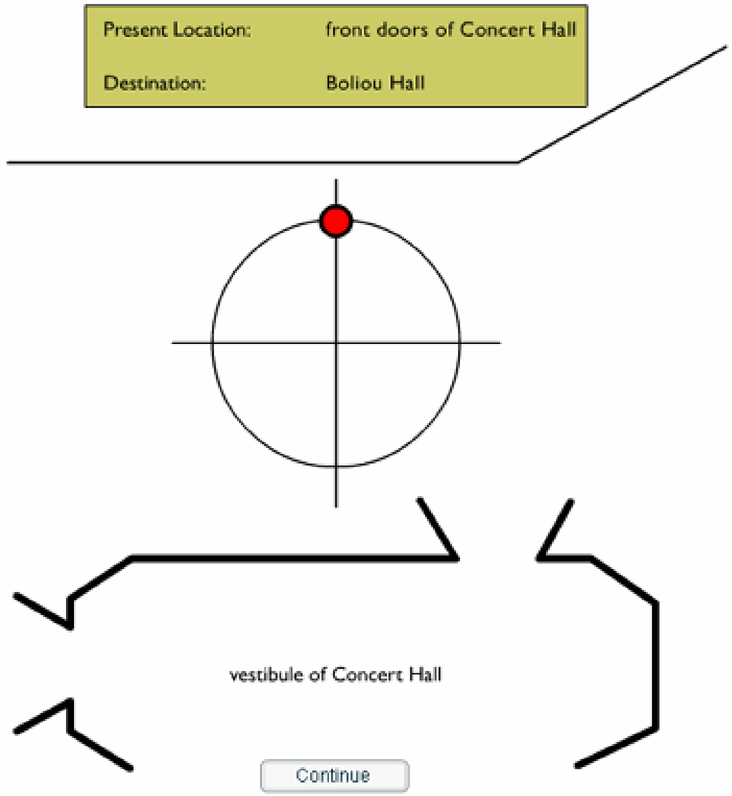


Continue

Present Location:	front door of Leighton Hall
Destination:	Hulings Hall



Continue



You have completed the Angle Measure Task.

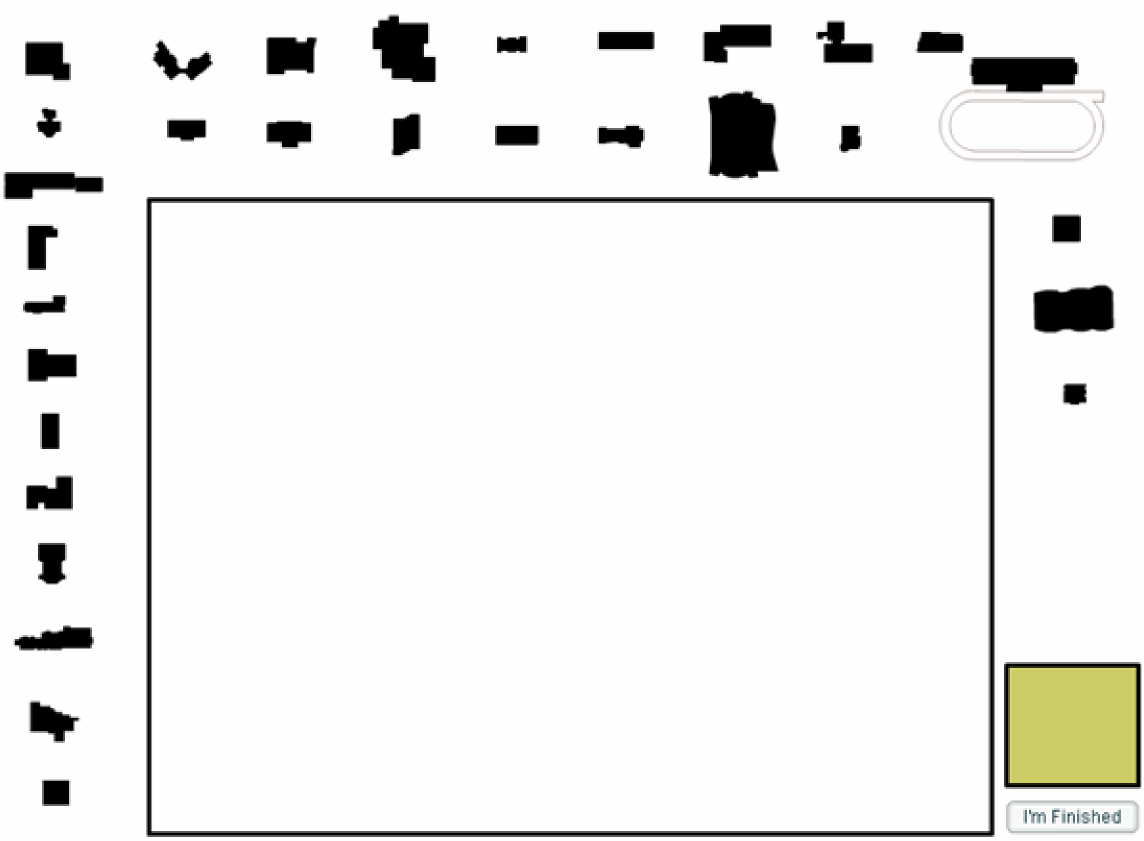
Continue

Cutout-Arrangement Task

On the following screen you will be provided with cutout pieces that represent buildings on the Carleton campus. When you place the mouse cursor on a cutout piece, its name will appear in the box located in the lower right corner of the screen. Please arrange the cutout pieces within the black border to best represent the respective locations of the buildings. To move a cutout piece, drag and drop it with the mouse. To rotate a cutout piece, place the cursor over the center of the cutout piece and press either the left or right arrow button on the keyboard. Once you have completed arranging all of the cutout pieces within the black border, press the Continue button.

If you have any questions, please ask the experimenter now.

Continue



You have completed the study.

Thank you for participating. The experimenter will now give you your compensation and answer any questions you may have about the study.

Appendix

Participant ID: ______

Participant Consent Form

Bringing Urban Form into Spatial Cognition and the Mind into Space Syntax

You are invited to participate in a research study of students' spatial understanding of the Carleton College campus being conducted by Drew Dara-Abrams (Cognitive Studies, Class of 2005, Carleton College). We ask that you read this form and ask any questions you may have before agreeing to be in the study. The study is focused on understanding how students store and represent their spatial knowledge of the Carleton campus. Participants will be asked to complete a set of computer-based questionnaires during one session. We are less interested in your individual knowledge than with the general representations and processes that are involved in human spatial cognition.

The records of this study will be kept private. In any sort of report we might publish, we will not include any information that will make it possible to identify a participant. Research records will be stored securely and only researchers will have access to the records. Your data will not be recorded together with your name, and any records that may uniquely identify you be destroyed at the conclusion of the study.

Participation in this study is entirely voluntary. If you decide to participate, you are free to not answer any question or to withdraw from the study at any time without penalty. Please feel free to contact the researcher Drew Dara-Abrams at (507) 663-7824 or daraabrd@carleton.edu with any questions. This study is being supervised by Dr. Kathleen M. Galotti, Department of Psychology, who is also available for answering any questions. Dr. Galotti can be contacted at (507) 646-4376 or kgalotti@carleton.edu.

The Institutional Review Board for Research with Human Subjects at Carleton College has reviewed and approved this study. You may also contact Louis Newman, Chair of the Institutional Review Board, at (507) 646-4224 or lnewman@carleton.edu with any questions or concerns you may have.

For your participation in the study you will receive a $5.00 gift certificate. If you decide to withdraw before completing the study, you will still receive the gift certificate.

By signing this form you confirm: that you are over 18 years old, that you understand your rights as a participant, that you understand what you have read, and that you are willing to participate.

____
Participant name (please print)

____
Participant signature

____/____/______
Date

Author Note

Drew Dara-Abrams, Cognitive Studies Program, Carleton College.

This research was supported by funding from the Cognitive Studies Program and the Dean of the College, both at Carleton College. Thank you to, among others, Kathie Galotti, Roy Elveton, Richard Strong, my comps group, the Carleton students who participated in my two studies, Sarah Horowitz, Geoff Findlay, Julie Butkowski, Miranda Blue, Susannah Lewis, and Alec, Benay, and Cassie Dara-Abrams.

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