Environmental influences on spatial memory: A study with Space Syntax

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Abstract

In this study we employed Space Syntax techniques to investigate the relation between environmental properties and spatial memory resulting from navigation of an unfamiliar environment. Participants first navigated two main routes in a virtual environment, memorizing the names and locations of buildings in them, and then carried out from memory a pointing task and a model-building task. In the pointing task, participants pointed more accurately to locations of high than low connectivity and integration. However, they pointed less accurately from locations of higher than lower connectivity and integration. This finding can be contextualized by broader memory phenomena (namely, the *fan effect*), whereby the ease of retrieval of a piece of information depends on its connections with other information. Additionally, both memory tasks here provide evidence that participants maintained the two routes they experienced as distinct representations. Together, our findings suggest that space syntax metrics, such as the connectivity and integration of locations, along with other environmental properties we explore (e.g., whether locations are experienced along the same route or not, and whether locations are intervisible) account well for the way spatial information is stored in and retrieved from memory.

Keywords: navigation, unfamiliar virtual environment, spatial memory, pointing task, space syntax

Environmental influences on spatial memory

In the course of their everyday life people navigate familiar and unfamiliar environments, processing information about the locations of buildings and the spatial relations among them. This information is stored in mental representations that allow people to perform a variety of spatial actions, such as finding their way in a city, computing shortcuts, providing directions to others, and more. One major undertaking in spatial cognition research is to understand the factors that influence the organizational structure of mental representations of space (see McNamara, 2003 for a review; also Avraamides & Kelly, 2008).

A number of studies have shown that environmental characteristics, such as the spatial arrangement of buildings and other features of space influence the way people represent spatial information in memory. For example, Werner and Schmidt (1999) demonstrated that the intrinsic axes formed by streets in a familiar city influence the organization of spatial memory. In their study, participants were asked to imagine themselves at the intersection of two major streets of their city while facing in different directions, and to point towards various landmarks. Participants pointed to buildings faster and more accurately when the imagined heading they adopted was aligned with one of the major streets in the intersection compared to all other imagined headings. This finding suggested that, to respond, people relied on a memory representation that was organized around the reference axes formed by the main streets of the intersection.

Similarly, in experiments using smaller scale configurations that involved a salient environmental reference frame, Shelton and McNamara (2001) showed that people represent spatial information in memory from a specific direction that is determined by the salient environmental cues. In one experiment, Shelton and

McNamara (2001) asked participants to study the locations of 7 objects placed on a carpet in a rectangular room, from two observation points, one that was aligned with the carpet and the walls of the room and one that was misaligned from that orientation by 135°. Participants then carried out judgments of relative direction from imagined perspectives (i.e., responding to trials in the form: “Imagine you are standing at X, facing Y; Point to Z”, where X, Y, and Z were objects from the memorized layout). Performance was faster and more accurate when responding from the perspective that was aligned with the carpet and the walls of the room compared to responding from all other perspectives, including the misaligned perspective participants had physically adopted (at 135°). Like the study of Werner & Schmidt (1999), this result suggests that environmental cues influence how people select and mentally represent a spatial layout in memory.

Although these and other studies (e.g. Galati & Avraamides, 2015; Mou & McNamara, 2002; Tverksy, 1981) provide evidence that properties of the environment can influence the selection of reference frames for encoding information in spatial memory, it is still largely unknown how other properties of space can predict performance in spatial memory tasks. The aim of this study is to provide a first step toward addressing this issue by examining the relationship between spatial memory and formal environmental properties.

Our approach involves using Space Syntax, (Bafna, 2003; Klarqvist, 1993; Koohsari, Kaczynski, McCormack & Sugiyama, 2014; Hillier & Hanson, 1984; Hillier, 2007; Syntax, 2004; Turner, 2004; Turner, 2007), an architectural research tool that has been leveraged by other researchers to investigate the relationship between properties of space and human behavior within that space (Franz & Wiener, 2005; Law et al., 2013). Specifically, in the present study we use the Axial Map Analysis, a

Space Syntax Analysis (Syntax, 2004) that translates spatial layouts into simple and precise mathematical graph representations by considering topological properties between spatial units (Bafna, 2003; Penn, 2003; Franz & Wiener, 2005; Wiener & Franz, 2005). The Axial Map refers to a graphical representation of the structure of space, where visible roads are represented as axial lines. Axial lines are the fewest and longest straight lines of sight from a specific location in space (Desyllas & Duxbury, 2001). Each axial line is called a node and represents the potential movement of a navigator through space (Syntax, 2004). Once constructed by graphing its constituent nodes, an Axial Map can be analyzed in terms of properties such as *integration* and *connectivity*.

Integration is a global measure that reflects the relative accessibility of an environment by recording the number of turns one needs to make to reach one location from another location and provides information about how well individual nodes are interconnected with the graph as a whole (Dara-Abrams, 2005). Nodes that can be reached more easily (through fewer turns) from many other nodes have high integration values and are often referred to as “shallow”, while nodes that are more difficult to reach (involving more turns) have lower integration values and are considered “deeper” (Klarqvist, 1993; Turner, 2004; Kostakos, 2010).

Connectivity is a local measure that refers to the number of other nodes that intersect a given node, or put more simply, the number of direct connections that each node has to other nodes (Nubani & Wineman, 2005; Syntax, 2004; Turner, 2004). A high connectivity value indicates that a node is connected to many other nodes, whereas a low value means that it has only few connections (Turner, 2004).

Metrics derived from Axial Map Analysis permit researchers to explore the relationship between environmental properties and spatial behavior or performance.

For instance, integration and connectivity, which are generally correlated with each other (Turner, 2004), have been shown to predict various aspects of spatial behavior, such as wayfinding (Bafna, 2003; Haq & Zimring, 2003) and route choice (Emo, Hoelscher, Wiener, & Dalton, 2010). For example, in a study by Emo et al. (2012) participants were asked to make left vs. right route decisions at urban street corners shown in photographs. Results showed that participants chose more often the turn toward the more connected and integrated streets, as quantified by Space Syntax. This finding suggests that Space Syntax measures can indeed capture spatial behavior.

Further support for this is provided by a study from Dara-Abrams (2005) who examined whether integration correlates with spatial memory about a familiar environment. In this study, Dara-Abrams used 12 pairs of buildings from the participants' campus, with buildings selected to come from axial lines with contrasting integration values, according to an Axial Map Analysis; that is, with one building of the pair being located on a high integration street and the other on a low integration street. Participants, then, carried out two spatial memory tasks. The *pointing task* required that participants imagine themselves standing next to one building of the campus and point to the other building from that pair. The *model-building* task required participants to create a model of the campus by dragging and dropping the pictures of the buildings on a rectangular outline presented on the computer screen. In the pointing task, when participants imagined standing at well-integrated-buildings, they pointed more accurately to the other buildings (of low integration) compared to when they stood at low-integration buildings. Likewise, in the model-building task, the integration value of a starting building significantly predicted the error in degrees of the angle between that and another building with high integration values associated with smaller error.

The study of Dara-Abrams (2005) suggests that environmental properties quantified through Space Syntax are reflected in the spatial representations of the environment that people construct. However, the fact that a familiar environment was used in that study leaves open the possibility that the results may not generalize to other contexts. For instance, Dara-Abrams's (2005) finding that people pointed more accurately from buildings in well-integrated routes and created a better map-representation for them could be due to the fact that they had walked those routes more often. Thus, when examining the spatial representations of familiar environments, it's impossible to dissociate the relative contribution of environmental properties (e.g., the degree of integration among buildings) from the level of actual experience people have with particular routes, especially since previous research shows that when making wayfinding decisions, people prefer taking highly-integrated streets (Emo et al., 2012). The present study overcomes this limitation by investigating whether space syntax measures can predict spatial memory performance for an *unfamiliar* environment i.e., an environment that was experienced for the first time during the experiment.

In our study, participants navigated two main routes in a virtual model of an unfamiliar university campus (Figure 1). Various buildings were encountered in each route but participants were asked to memorize the names and locations of four buildings that were identified by their names posted on signs in front of them (Figure 2). Once they navigated the two main routes, participants navigated two additional routes that provided connections between the two initial routes. Next, participants completed two memory tests. In the pointing task, they carried out a series of trials in which, after being teleported in front of a landmark building in the virtual environment, they pointed to the location of another building (Figure 3). The two

buildings in each pointing trial could be located either on the same route or on different routes. In the model-building task, participants had to drag and drop the pictures of the eight buildings (shown from a top-down perspective) into a rectangle on their computer screen in order to create a map of the virtual environment they had experienced (Figure 4). Finally, participants completed the Santa Barbara Sense of Direction (SBSOD) questionnaire, a self-report measure of spatial ability.

Using Axial Map Analysis we computed the connectivity and integration values for each building in the environment in order to assess how these values related to performance in the spatial memory tasks. In addition to these metrics, we also examined the influence of two additional environmental factors: whether buildings were experienced as part of the same or different routes, and whether buildings were visible from each other if on the same route. By comparing performance pertaining to the same vs. different routes (i.e., of pointing performance for pairs from the same vs. different route, and of models reconstruction performance for the set of buildings from the same vs. different route), we can gain insight into whether participants integrated the two routes into a single spatial representation or kept them separate in memory (see Adamou, Avraamides, & Kelly, 2013; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014).

We made the following main predictions:

1. We expected that the integration scores from the axial map analysis would predict performance for the pointing task¹. Using pairs of buildings with

¹ We are not examining how Space Syntax values would predict performance on the model building task, since that task yields a single measure of performance for the entire environment (or alternatively, a score for each of the subsets of buildings from the two routes), making it impossible to assess the relationship between task performance and measures of connectivity and integration associated with the individual landmarks in the environment.

contrasting integration values, Dara-Abrams (2005) found that participants pointed more accurately from building of high integration to buildings with low integration than vice-versa. Thus, better performance could have resulted from either the high integration of the standing location or the low integration of the target location. We expect that our results will allow us to resolve this ambiguity, albeit for a newly-learned environment. Of interest would be to see whether, beyond integration, connectivity is also predictive of pointing performance; this has yet to be explored in the literature.

- 2a. We expected that pointing to buildings within the same route would be more accurate than pointing to buildings across different routes. This prediction follows previous studies indicating that people typically maintain spatial information from separate routes or spatial arrays in separate representations (e.g., Weisberg et al., 2014, which used the same virtual environment as here, as well as Ishikawa & Montello, 2006; Meilinger, Berthoz and Wiener, 2011; Pantelides & Avraamides, 2016; Weisberg & Newcombe, 2016; but see Moar & Carleton, 1982). Such a finding would support the hypothesis that people encode spatial relations hierarchically (Hirtle & Jonides, 1985) and replicate the results of previous studies using pointing tasks (e.g., Weisberg & Newcombe, 2016).
- 2b. Following the reasoning outlined above, we expected that performance on the model building task would be inferior for the entire model (with all eight buildings) than for each of the two routes (with subsets of four buildings), providing further support for the maintenance of separate spatial representations in memory. Such a finding would replicate conceptually, by using a task other than pointing, the prior finding that spatial relationships

among landmarks experienced in separate routes are not well integrated in a single representation.

Method

Participants

Sixty-five students (19 male) from the University of Cyprus, with mean age of 21.6 years ($SD= 3.6$ years), participated in the experiment. Twenty-nine participants received course credit for participating, while the remaining participants received a small monetary reimbursement (10€). All participants signed an informed consent form before the experiment session and were thoroughly debriefed afterwards.

Materials

The virtual environment

The experiment employed the Virtual SILCton, a virtual model based on the Ambler campus of Temple University, created in the Unity3D engine (www.unity3d.com; for more information see Galati, Weisberg, Newcombe, & Avraamides, 2017; Schinazi, Nardi, Newcombe, Shipley & Epstein, 2013, and Weisberg et al., 2014). The virtual environment was projected on a large 295 cm by 180 cm projection screen and was viewed by participants sitting in front of it at a distance of 200 cm. Participants navigated the environment using the keyboard and the mouse. Simulated movement was effected through the arrow keys on the keyboard, while the mouse was used to rotate the viewpoint up to 360° horizontally and 120° vertically.

Self-Report Measure of Spatial Ability

To capture individual differences in spatial ability, participants completed the Santa Barbara Sense of Direction (SBSOD) at the beginning of the experiment (Hegarty et al., 2002). SBSOD is a unidimensional measure of sense of direction,

consisting of 15 items in a 7-point Likert scale, with Cronbach's $\alpha = .89$. It measures how strong a navigator participants feel they are, with lower scores indicating lower navigation ability (sample: "I usually remember a path that I have walked once"). We expected that participants with higher self-reported ability would perform better on the memory tasks (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002; Weisberg et al., 2014). Moreover, it is possible that individuals of different spatial ability may be differentially impacted by the integration and connectivity of locations in the environment. However, since this possibility is not motivated a priori by some theoretical account, our examination of the relationship between spatial ability and task performance was exploratory.

Space Syntax measures

An axial map analysis of the virtual environment was performed using the DepthmapX software (Varoudis, UCL/UCL's Space group, 2004). Once the medium resolution axial map model was created (including only the roads that were visible to participants during navigation), integration (Figure 5) and connectivity (Figure 6) values were computed for each node in the environment. Each building was assigned the integration and connectivity value of the node on which the main entrance of that building was located.

Design and Procedure

First, participants spent a few minutes becoming familiar with the virtual environment and the controls for moving in it and looking around. Once they had indicated comfort and familiarity, they proceeded to the study phase. During this phase, they were asked to navigate four different routes, first the two main and then the two connector routes. Each of the main routes contained 4 landmark buildings, the names and locations of which participants had to memorize. Each of the connector

routes led participants from one main route to the other, providing information on how the routes were spatially related to each other in the environment. For all routes, participants travelled from the start to the finish and back, following arrows on the ground, and had unlimited time to complete navigation.

The landmark buildings that participants were asked to remember in the main routes were marked with a blue diamond that hovered in the middle of the road (Figure 2), while the name of each building was written on a signpost in front of each building (the blue diamond was intended to alert participants that they were approaching a landmark building). Prior to navigating the two connector routes, participants were instructed to pay attention to how the two main routes were connected. The connector routes did not involve any additional buildings other than the 8 buildings learned in the two main routes. The presentation order of the two main routes and the two connector routes was counterbalanced across participants, with each participant experiencing one of the following route orders: ABCD, ABDC, BACD, BADC, where A and B indicate the identity of the two main routes, and C and D the identity of the two connector routes.

Following the study phase participants started the testing phase, which involved two memory tasks. In the pointing task that was carried out first, participants were teleported in front of one of the buildings in the virtual environment, initially having the entrance of that building behind them and facing in a random direction. They were asked to point to the direction of other buildings (e.g. “Point to Harvey House”), by rotating in the horizontal plane a crosshair that appeared on the center of the screen linked to the viewpoint (Figure 3). The order of the standpoints from which participants pointed followed the order in which the buildings were encountered during the study phase, whereas target buildings appeared in a randomized order. The

task was completed when participants had pointed from all 8 buildings to all other buildings. This resulted in a total of 56 trials. Pointing error was measured by computing the angular deviation of participants' response from the correct response.

In the model-building task that followed, participants constructed from memory a model of the virtual environment they had experienced. A rectangular frame was shown on the screen along with top-down perspective pictures of the eight buildings beneath it (Figure, 4). Participants were told that the rectangular frame represented the entire virtual environment they had navigated and that they should drag and drop each building at the correct location in it. Participants could adjust the building positions as much as they needed to. Performance on the model-building task was assessed using bidimensional regression analysis (Friedman & Kohler, 2003; Tobler, 1994), which involves a Euclidean transformation to the set of dependent A-B points (the participant's placement of the buildings) to match the fixed independent X-Y points (the veridical coordinates of the buildings).

Results

Our analytic approach involved, first, examining the relation between Space Syntax measures and performance in the pointing task through correlations and t-tests, in order to examine whether integration and connectivity were associated with better performance (Prediction 1). Then we further examined, through ANOVAs, whether performance on the pointing task differed across the between- and within-route pointing judgments, (Prediction 2a). We also examined participants' performance on the model-building task using bidimensional regression analysis and ANOVAs to determine whether reconstructions were more accurate for subsets of buildings from the same vs. different routes (Prediction 2b). Finally, we conducted

exploratory analyses to examine the relation between SBSOD scores and performance in the memory tasks.

Relationship between Space Syntax measures and pointing performance

Since each building could appear in a pointing trial as either a target or a standpoint building, we analyzed pointing error with respect to the connectivity or integration of buildings as targets and as standpoints, separately.

To do so, we first computed for each participant a correlation coefficient, based on the connectivity or integration measure of that trial and pointing error, and then we averaged these correlation coefficients across participants to test whether the resulting mean correlation differed from zero. As noted, we performed this process twice: once for the connectivity and integration measures associated with the target buildings and once for those of the standpoint buildings of trials.

When considering target buildings, participants were more accurate when pointing to target buildings with high connectivity and integration. Indeed, an one sample t-test revealed a significant negative correlation ($r=-.43$, $SE=.045$) between pointing error and the target's connectivity, $t(64)=9.60$, $p=.001$. Similarly, a significant negative correlation ($r=-.33$, $SE=.042$) between pointing error and the target's integration was obtained, $t(64)=8.00$, $p=.001$.

However, when considering buildings that were the standpoint in the pointing task, a different picture emerged: participants were less accurate when pointing from buildings located in highly-connected and well-integrated nodes. This was corroborated by the presence of significant positive correlations between both pointing error and the standpoint's connectivity ($r=.24$, $SE=.043$)

and pointing error and the standpoint's integration ($r=.19$, $SE=.041$); $t(64)=5.43$, $p=.001$ and $t(64)=4.49$, $p=.001$ respectively.

Pointing performance within vs. between routes

Data were first analyzed using a mixed design repeated measures ANOVA, with trial type (same vs. different route) as a within-participants factor, and gender and route order as between-participants factors. The analysis revealed a significant main effect for the trial type with participants responding more accurately on trials involving buildings from the same route than on trials with buildings from different routes, $F(1, 57) = 56.80$, $p = .001$, $\eta^2 = .50$ (Table 1). Gender did not influence pointing performance, $F(1, 57) = 1.95$, $p = .17$, $\eta^2 = .03$ ($M=41.24$, $SE=1.27$ for female and $M=36.44$, $SE=3.33$ for male participants), nor did it interact with the trial type, $F(1, 57) = .43$, $p = .51$, $\eta^2 = .08$ (Figure 7).

To explore the possibility that the observed differences between the two trial types were due to the intervisibility of buildings from the same route, we recoded trials in terms of whether the target building was at least partially visible from the standpoint building. Thus, trials were recoded as involving buildings from different routes ($N= 32$), which were never intervisible, trials involving buildings from the same route that were intervisible (*seen trials*, $N= 17$) and trials involving buildings from the same route that were non-intervisible (*unseen trials*, $N= 7$). We then conducted an ANOVA with trial type (same-seen, same-unseen, different) as within-participants factor, and with gender and route order as between-participants factors. A significant effect of trial type was again obtained, $F(2, 114) = 44.97$, $p = .001$, $\eta^2 = .44$. Specifically, participants pointed more accurately in same-seen trials ($M= 23.63^\circ$, $SE= .95^\circ$) than same-unseen trials ($M= 40.31^\circ$, $SE= 1.56^\circ$), $F(1, 57) = 59.56$, $p = .001$, $\eta^2 = .51$, and different trials ($M= 48.30^\circ$, $SE= .92^\circ$), $F(1, 57) = 90.43$, $p = .001$, $\eta^2 =$

.61. Performance on same-unseen and different trials also differed, with performance on different trials being worse than on same-unseen trials, $F(1, 57) = 4.11, p = .05, \eta^2 = .07$, even though neither type of trials involved intervisible buildings. No other main effects or interactions were significant (Figure 8).

Collectively, these findings suggest that both the visibility of the buildings and whether they were experienced on the same route or not influenced participants' accuracy on the pointing task. Participants were more accurate when making judgments on trials involving buildings from the same (vs. different) route, even when intervisibility was factored into the analyses.

Performance on model-building task

To assess performance on the model-building task, we used bidimensional regression analysis (Friedman & Kohler, 2003; Tobler, 1994). In these analyses, a Euclidean transformation is applied to the set of dependent A-B points (the coordinates of the participant's placement of the buildings), such that they are optimally rotated, scaled, and translated to match the fixed independent X-Y points (the veridical coordinates of the buildings). The adjusted points are correlated with the correct locations, resulting in a correlation coefficient. Here, we use the correlation coefficient squared (R^2) as our dependent measure, which captures the proportion of variance explained in the actual layout of buildings by the participant's arrangement of buildings. We computed R^2 values for the entire model (8 buildings), as well as for the two subsets of four buildings from the individual main routes A and B.

We first examined performance for the entire model (all 8 buildings) through an ANOVA with route order and gender as between-participants factors. No main effects or interactions were significant. We also examined model-building performance by

taking route identity into account, in a mixed-design repeated-measures ANOVA, with route identity (Route A and Route B) as the within-participants factor, and route order and gender as between-participants factors. Again, no main effects or interactions were significant.

Finally, we considered performance on the model-building task relative to pointing performance. As shown in Table 2, participants mean pointing error was negatively correlated with model building performance for both Route A and Route B: the more accurate the placement of landmarks for Route A or Route B in the model building task (higher R^2), the smaller their overall error on the pointing task. Notably, the correlation between R^2 for the entire model and overall pointing error was not significant ($p = .32$). This finding—that the performance on the pointing task and on model building was correlated when routes were examined separately (but not together)—is congruent with the findings reported in the previous section—that performance in the pointing task was better on trials with buildings from the same route than from different routes. Together, these findings suggest that participants had maintained the routes in separate representations.

Individual differences in self-reported spatial ability and memory performance

Surprisingly, as shown in Table 2, self-reported spatial ability, as captured by the SBSOD questionnaire, was not correlated with any aspect of spatial memory performance.

Discussion

In this study, we examined the relationship between spatial memory for a newly experienced environment and properties of that environment. After navigating an unfamiliar virtual environment, participants' performance on a pointing and a

model-building task was impacted by formal environmental properties obtained from an axial map analysis from the Space Syntax framework. We found that participants pointed more accurately to highly integrated and connected locations. Perhaps surprisingly, participants were also less accurate to point *from* locations with high connectivity and integration to other locations. These results suggest that properties of environmental space influence the way information is stored or retrieved from spatial memory. Still, the fact that the correlations between the Space Syntax measures and pointing accuracy were in the opposite direction for target vs. standpoint locations is intriguing and requires some unpacking.

A possible account for the dissociation in pointing performance when target vs. standpoint locations are considered is the presence of a fan effect, a well-documented phenomenon from memory research. According to this account as the number of memory traces associated with a concept increases, the longer it takes to retrieve each one of the traces due to interference from the rest (Bunting, Conway, & Heitz, 2004). Similarly, here, when retrieving spatial locations from a standpoint, it could be that as that location is increasingly related to other locations (i.e., the standpoint is a highly integrated and connected landmark), the more difficult it is to retrieve with accuracy each of those locations. In contrast, highly integrated/connected landmarks are localized (as targets) with greater precision than less integrated/connected landmarks due to having more information associated with them (i.e., more connections to other landmarks).

This pattern of results, which we have framed as instantiating a fan effect, contrasts with previous findings that people perform more accurately from standpoints of high integration than from standpoints of low integration (Dara-Abrams, 2005). This discrepancy could be due to a number of methodological

differences between our study and that of Dara-Abrams (2005). For example, in that study the environment used was familiar to participants, whereas in our study the environment was unfamiliar. Moreover, in Dara-Abrams's study the pointing trials always involved pairs of buildings with high-low integration, whereas in our study trials involved pairs of buildings with variable integration and connectivity. Finally, there were differences in how the imagined perspective could be adopted in the pointing task. In Dara-Abrams's study, the task was arguably more difficult, as participants were asked to adopt perspectives from memory by imagining themselves standing in front of buildings in their campus, whereas in our study participants were placed at the actual standpoint in the virtual environment, having visual access to the immediate surroundings of the standpoint and being able to rotate their viewpoint. All these methodological differences could have contributed to the relatively more accurate performance from highly integrated standpoints in Dara-Abrams (2005).

Altogether, our findings highlight that environmental properties derived from Space Syntax can predict certain aspects of spatial memory, extending previous work that has documented that these metrics can predict on-line wayfinding decisions (e.g., Emo et al., 2010). Our findings also add to the growing literature that underscores the importance of environmental factors in representing spatial information in memory. For example, according to one popular theory of spatial memory proposed by McNamara and colleagues (e.g., McNamara, 2003; Mou, McNamara, Valiquette, & Rump, 2004), when people make spatial judgments, they access spatial relations in memory representations that are stored with a preferred organizing direction. Although the preferred direction is very often determined by egocentric experience (Richard & Waller, 2013; Shelton & McNamara, 2001), it can also be established based on environmental cues, such as the environment's geometry (Shelton &

McNamara, 2001), the intrinsic features of the spatial configuration arising from its symmetry (Galati & Avraamides, 2015; Li, Carlson, Mou, Williams, & Miller, 2011; Mou & McNamara, 2002) and orthogonality (Richard & Waller, 2013), as well as by functional features of landmarks in the configuration (Taylor & Tversky, 1992). The presence of such salient environmental cues can override egocentric experience so that people can in fact maintain spatial information from orientations that have not been experienced (Shelton & McNamara, 2001). In line with this work, our findings also demonstrate that environmental properties influence the accuracy with which information is maintained or retrieved.

Another facet of our findings underscores that navigators do not readily integrate information from routes they've experienced separately into a single representation. Participants, here, pointed more accurately on trials involving buildings from the same route than from a different route. Moreover, their pointing performance on trials with buildings from a given route was correlated with model-building performance for the subset of buildings from that route. Importantly, these correlations were not reliable when performance in each task was considered as a whole. Both findings support the idea that when people study routes or spatial layouts with spatial and temporal separation, they typically maintain them in distinct representations (Meilinger, Berthoz & Wiener, 2011; Pantelides & Avraamides 2016; Weisberg et al., 2014; Weisberg & Newcombe, 2016; but see Moar & Carleton, 1982). These findings are also in line with hierarchical accounts of spatial memory (Hirtle & Jonides, 1985; see also Greenauer & Waller, 2010), which propose that locations can be maintained in separate clusters whose spatial relations are represented at different levels in a hierarchy. Such accounts support cognitive

economy by reducing the number of spatial relations that need to be stored in memory.

Notably, performance in the pointing and the model building task was not predicted by scores on the SBSOD scale. Although the lack of a correlation with SBSOB was somewhat unexpected, it is in fact in line with results reported by Hegarty et al. (2002; Exp. 3): in that study, SBSOD scores predicted pointing performance to familiar landmarks (on the participants' campus) but not to unfamiliar locations (for newly learned objects in the laboratory). One explanation put forward by Hegarty et al. (2002) was that this was the case because the location of the landmarks was learned over time by navigation whereas the laboratory objects were newly learned and that SBSOD might be better suited to capture real-life navigation and wayfinding than memory performance about newly acquired spatial knowledge.

Overall, our findings highlight the importance of environmental factors on spatial memory by demonstrating that properties of environmental space, as captured by Space Syntax metrics, relate to performance on spatial judgments from memory. In our study, participants pointed more accurately *to* highly integrated and connected locations but at the same time they were less accurate to point *from* locations with high connectivity and integration to other locations. Although this is intriguing finding calls for further research, it provides clear evidence for the role of environmental cues in the organization and access of spatial information in memory. Performance in both the pointing and model-building tasks of our study also supports the hierarchical organization of spatial memory: the finding that navigators were more efficient to reason about locations experienced within the same route than across routes suggests that they had maintained distinct representations for the two routes. Together, our findings underscore that experience with a spatial environment interacts

with environmental properties to determine how spatial information is encoded and maintained in memory.

References

- Adamou, C., Avraamides, M. N., & Kelly, J.W. (2013). Integration of visuo-spatial information encoded from different viewpoints. *Psychonomic Bulletin & Review*, 126, 244-246.
- Avraamides, M. N., & Kelly, J. W. (2008). Multiple systems of spatial memory and action. *Cognitive Processing*, 9, 93-106.
- Bafna, S. (2003). Space Syntax: A brief introduction to its logic and analytical techniques. *Environment and Behavior*, 35, 17-29.
- Bunting, M. F., Conway, A. R., & Heitz, R. P. (2004). Individual differences in the fan effect and working memory capacity. *Journal of Memory and Language*, 51, 604-622.
- Dara-Abrams, D. (2005). Architecture of mind and world: How urban form influences spatial cognition. *Environment and Behavior*, 23, 47-69.
- Desyllas, J., & Duxbury, E. (2001). Axial maps and visibility graph analysis. *In the Proceedings of the 3rd International Space Syntax Symposium* (Vol. 27, pp. 21-13), Georgia Institute of Technology Atlanta.
- Emo, B., Hoelscher, C., Wiener, J., & Dalton, R. (2012). Wayfinding and spatial configuration: evidence from street corners. *In Proceedings of the 8th International Space Syntax Symposium* (pp. 1-16), PUC, Santiago de Chile.
- Franz, G., & Wiener, J. M. (2005). Exploring isovist-based correlates of spatial behavior and experience. *In Proceedings of the 5th International Space Syntax Symposium Delft*, NL. TU Delft Press.
- Friedman, A., & Kohler, B. (2003). Bidimensional regression: assessing the configural similarity and accuracy of cognitive maps and other two-dimensional data sets. *Psychological Methods*, 8, 468.

Galati, A., Weisberg, S. M., Newcombe, N. S., & Avraamides, M.N. (2018).

When gestures show us the way: Co-speech gestures selectively facilitate navigation and spatial memory. *Spatial Cognition and Computation*, 18, 1–30. DOI: 10.1080/13875868.2017.1332064

Galati, A., & Avraamides, M. N. (2015). Social and representational cues jointly influence spatial perspective-taking. *Cognitive Science*, 39, 739-765.

Greenauer, N., & Waller, D. (2010). Micro-and macrorference frames: Specifying the relations between spatial categories in memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36, 938-957.

Haq, S., & Zimring, C. (2003). Just down the road a piece the development of topological knowledge of building layouts. *Environment and behavior*, 35, 132-160.

Hegarty, M., Richardson, A. E., Montello, D. R., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence*, 30, 425-447.

Hillier, B., & Hanson, J. (1984). *The social logic of space* (Vol. 1, p. 1984). Cambridge: Cambridge University Press.

Hillier, B., & Vaughan, L. (2007). The city as one thing. *Progress in Planning*, 67, 205-230.

Hirtle, S.C., & Jonides, J. (1985). Evidence of hierarchies in cognitive maps. *Memory & Cognition* 13, 208–217.

Ishikawa, T., & Montello, D. R. (2006). Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned spaces. *Cognitive Psychology*, 52, 93–129.

- Klarqvist, B. (1993). A space syntax glossary. *Nordisk Arkitekturforskning*, 2, 11-12.
- Koohsari, M. J., Kaczynski, A. T., McCormack, G. R., & Sugiyama, T. (2014). Using Space Syntax to Assess the Built Environment for Physical Activity: Applications to Research on Parks and Public Open Spaces. *Leisure Sciences*, 36, 206-216.
- Kostakos, V. (2010). Space syntax and pervasive systems. In *Geospatial analysis and modelling of urban structure and dynamics* (pp. 31-52). Springer Netherlands.
- Law, S., Stonor T. & Lingawi, S. (2013). Measuring The Impact Of Spatial Layout Design Using Space Syntax. In *Proceedings of the 9th International Space Syntax Symposium*. Seoul. 061 (pp. 1-14).
- Li, X., Carlson, L. A., Mou, W., Williams, M. R., & Miller, J. E. (2011). Describing spatial locations from perception and memory: The influence of intrinsic axes on reference object selection. *Journal of Memory and Language*, 65, 222–236.
- McNamara, T. P. (2003). How are the locations of objects in the environment represented in memory?. In *Spatial cognition III* (pp. 174-191). Springer Berlin Heidelberg.
- Meilinger, T., Berthoz, A., & Wiener, J. M. (2011). The integration of spatial information across different viewpoints. *Memory & Cognition*, 39, 1042-1054.
- Moar, I., & Carleton, L. R. (1982). Memory for routes. *The Quarterly Journal of Experimental Psychology*, 34, 381-394.

- Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28, 162-170.
- Mou, W., McNamara, T. P., Valiquette, C. M., & Rump, B. (2004). Allocentric and egocentric updating of spatial memories. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 30, 142–157.
- Nubani, L., & Wineman, J. (2005). The role of space syntax in identifying the relationship between space and crime. *In Proceedings of the Fifth International Space Syntax Symposium*. Delft, (pp. 413 – 422).
- Pantelides, S. N., Kelly, J. W., & Avraamides, M. N. (2016). Integration of spatial information across vision and language. *Journal of Cognitive Psychology*, 28, 171-185.
- Penn, A. (2003). Space syntax and spatial cognition or why the axial line?. *Environment and Behavior*, 35, 30-65.
- Richard, L., & Waller, D. (2013). Toward a definition of intrinsic axes: The effect of orthogonality and symmetry on the preferred direction of spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39, 1914–1920.
- Schinazi, V. R., Nardi, D., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2013). Hippocampal size predicts rapid learning of a cognitive map in humans. *Hippocampus*, 23, 515–528.
- Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive Psychology*, 43, 274-310.
- Syntax, S. (2004). Fifth framework Programme: AGORA cities for people.

- Taylor, H. A., & Tversky, B. (1992). Descriptions and depictions of environments. *Memory and Cognition*, 20, 483–496.
- Tobler, W. R. (1994). Bidimensional regression. *Geographical Analysis*, 26, 187-212.
- Turner, A. (2004). *Depthmap 4 - A researcher's handbook*. Bartlett School of Graduate Studies, UCL, London.
<http://www.vr.ucl.ac.uk/depthmap/depthmap4.pdf>
- Turner, A. (2007). UCL Depthmap 7: From isovist analysis to generic spatial network analysis. *New Developments in Space Syntax Software*, Istanbul Technical University, 43-51.
- Tversky, B. (1981). Distortions in memory for maps. *Cognitive Psychology*, 13, 407-433.
- Weisberg, S. M., Schinazi, V. R., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 40, 669.
- Weisberg, S. M., & Newcombe, N. S. (2016). How do (some) people make a cognitive map? Routes, places, and working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 42, 768.
- Werner, S., & Schmidt, K. (1999). Environmental reference systems for large-scale spaces. *Spatial Cognition and Computation*, 1, 447-473.
- Wiener, J. M., & Franz, G. (2005). Isovists as a means to predict spatial experience and behavior. *Spatial Cognition IV. Reasoning, Action, Interaction* (pp. 42-57). Springer Berlin Heidelberg.

Figure 1. Schematic map for the virtual environment with the 4 routes and the critical buildings. Solid lines indicate Main Routes and dashed lines Connecting Routes.

Figure 2. A landmark building in the main route marked with a blue diamond and named on a signpost.

Figure 3. Screenshot from the Pointing Task. Participants could rotate their viewpoint and the crosshair attached to it using the mouse.

Drag and drop the pieces into the box to create a model of the virtual world. Use the entire space of the box.

Figure 4. Model-building task. Participants dragged and dropped buildings into the rectangular frame.

Figure 5. Integration measurement from the axial map analysis.

Figure 6. Connectivity measurement from the axial map analysis.

Figure 7. Pointing error as a function of gender and the type of route. Error bars represent standard errors of the mean from the ANOVA.

Figure 8. Pointing error as a function of gender and trial type. Error bars represent standard errors of the mean from the ANOVA.

Table 1. Means and standard deviations for individual ability, model building performance, and Space syntax metrics across different route distinctions

	M	SD	N
SBSOD	4.41	.90	65
Pointing Error			
Same	28.70	12.9	65
Different	48.18	13.09	65
R ² from model building			
Route A	.54	.27	65
Route B	.57	.31	65
Entire Model	.43	.24	65
Space Syntax measures			
Route A			
Connectivity	2	0.9	6*
Integration	1.06	0.5	6
Route B			
Connectivity	4.2	1.5	10
Integration	2.5	1.4	10
Entire Map			
Connectivity	3.71	1.9	16
Integration	1.40	.36	16

Note. For Space Syntax measures, N refers to nodes of axial map analysis

Table 2. Bivariate correlations between measures of individual ability (SBSOD), model-building (R^2) and pointing error (N=65)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
1. SBSOD	-												
2. R^2 Entire model	-.027	-											
3. R^2 Route A	.071	-.051	-										
4. R^2 Route B	.163	.085	.183	-									
5. Mean Pointing Error	-.054	-.125	-.389***	-.404***	-								
6. Pointing Error Same	-.110	-.085	-.388***	-.465***	.785***	-							
7. Pointing Error Different	.004	-.116	-.272*	-.237*	.876***	.349**	-						
<i>Same route pointing trials</i>													
8. Pointing Error: Route A standpoint & target	-.081	-.006	-.320**	-.333**	.674***	.835***	.350**	-					
9. Pointing Error: Route B standpoint & target	-.109	-.120	-.362**	-.466***	.665***	.919***	.276*	.555***	-				
<i>Different route pointing trials</i>													
10. Pointing Error: Route A standpoint	-.101	.011	-.378**	-.301*	.821***	.699***	.663***	.555***	.555***	-			
11. Pointing Error: Route A target	.011	-.135	-.298*	-.313*	.916***	.548***	.911***	.606***	.399***	.667***	-		
12. Pointing Error: Route B standpoint	-.014	-.177	-.340**	-.405***	.944***	.671***	.859***	.494***	.666***	.588***	.913***	-	
13. Pointing Error: Route B target	-.124	-.074	-.419***	-.422***	.835***	.834***	.583***	.569***	.853***	.793***	.546***	.729***	-

Note. ns = not significant ($p > .05$), $p < .05^*$, $p < .01^{**}$, $p < .001^{***}$