The Effects of Boundary Manipulations on Navigational Abilities

A Thesis

Presented to

The Academic Faculty

by

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In Partial Fulfillment

of the Requirements for the Research Option in the

School of Computer Science

Georgia Institute of Technology

July 2020

Abstract

The purpose of this study is to see how manipulating boundaries impact one's spatial memory in unfamiliar spaces. To test this, after we measured our participants' Sense of Direction (SOD) and memory capacities, they were equally divided up into three separate training conditions: an abstract environment, a translucent environment, and a control environment. Afterwards, they were evaluated using wayfinding and pointing tasks. Our results indicated that the abstract training significantly impacted those with varying SOD's. Those with low SOD's in the control condition outperformed their abstract counterparts in wayfinding, and those with high SOD's in the opaque abstract condition outperformed their control counterparts in the pointing tasks. This could be due to their reliance on different navigation strategies. In this case piloting versus path integration, respectively. Regardless, this study emphasizes the need to further investigate other methods of boundary manipulation that will potentially affect people's spatial abilities.

Introduction

Spatial information can be defined as the information in our environment, such as, the landmarks, distances, etc. Varying presentations of spatial information can have a significant impact on the way we encode and store such information (Horner, Bisby, Wang, Bogus, & Burgess, 2016; Mou & Wang, 2015). For example, if one were to walk through a house, the way he or she would remember information about objects in the house could be greatly affected by several factors. E.g., the order of presentation, the time between each object, and the boundaries between each object. Research has also shown that these physical boundaries can greatly affect the way one might remember these objects in relation to one another (Radvansky & Copeland, 2006). For example, one might easily remember a room filled with a certain number of objects. However, when boundaries are enforced between objects, the individual's memory of the same objects could vastly differ from when those boundaries are absent. These boundaries segment the continuous experience into separate memories, and information retrieval can be impaired as a result. In the current study, we aim to investigate whether the effects of boundaries on memory can be overcome by rendering the boundaries or barriers translucent and abstracting their details.

Extensive research has been done on how boundaries can affect how memory is categorized and encoded. In a prior study (Meilinger, Strickrodt, & Bülthoff, 2016), the authors discussed how people represent spaces of different scales, namely the vista and environmental spaces. Vista space is the space where all the objects can be observed from one vantage point, and environmental space is the space where the navigation is required to observe all the information. Meilinger examined the differences in learning the layout of objects in a vista space and in an environmental space with the introduction of boundaries. For the experiment, they placed the participants in a vista environment in fixed positions where they could view all objects simultaneously. In the environment space, hallways were positioned to physically separate objects in the given space, forcing participants to navigate around to see all the objects. In both experiments the positions of the objects were the same, but the introduction of the boundaries was different. The results of the experiment depicted how the introduction of boundaries had a significant impact on the participants' ability to encode the location of the objects in memory. Usually participants tend to perform better in the original reference angle they were placed in the environment (in this case the 0°). However, since the boundaries were generally placed at angles oblique to the participant's reference, the participant would recall objects better at positions oblique to the reference angle after traversing the environment. The order the participant recalled the objects positions was also affected by the introduction of boundaries. Most of the participants in the control condition remembered objects mostly in a random order, but those in the experiment group would remember the objects in the order they encountered them through the hallways. Subsequent experiments in this study demonstrated how the introduction of the boundaries was the primary actor in the change in encoding, not other factors, such as movement.

Another study conducted by Horner, A. J., et al. (2016) also highlighted how the spatial relation of objects had a significant impact on memory. For this experiment, they placed objects in both the same room and rooms adjacent to each room. Participants were presented a series of objects in sequence, with some of the next objects being in the same room and some in the next room. The results of the experiment showed how that participants could better identify the next object in sequence when the object was in the same room compared to objects which were separated by the same distance but located in different rooms. This phenomena was also the case even with additional experiments where they controlled for the appearance of the environment the object was presented in, the distance the objects were placed apart from each other, and the time the next object was presented for objects that were presented in the same room as the previous one. Both experiments highlight how the spatial memory and the encoding of such information is strongly affected by physical barriers.

However, neither of these experiments address the effects boundary manipulations have on one's spatial memory. For our study, we manipulate the boundaries' translucency and textural detail to see if participants can remember the position of objects better than in a control environment composed of opaque realistic boundaries. A study conducted by Radvansky and Copeland (2006) has shown how people's memories of objects are impaired across opaque boundaries. However, does the same still apply for translucent boundaries? A study (Gianni, De Zorzi, & Lee, 2018) has conducted something similar with children, but is only tangentially related to how translucency manipulations affect memory. In contrast to her small test space, we put our participants in larger city-like virtual space. These spatial manipulations ensure that our environment is both naturalistic and complex, allowing us to observe the practical contributions of learning to navigate a new space and the theoretical contributions of how translucent or abstract boundaries affect humans. Since no published study has examined how either of these effects impact spatial learning, our study can help us better understand how humans perceive and represent boundaries and whether it varies across individuals.

Thus, we wish to see if people with high sense of direction can benefit from translucent or abstract boundaries, and if people with a low sense of direction do not benefit by placing participants in a realistic city environment in virtual reality and testing these manipulations on them. In the case of positive benefit, our findings could change the way that we approach spatial training. One approach could be possibly integrating into virtual reality training simulations or integration into navigation tools commonly used today

Literature Review

Boundaries play a crucial role in the everyday process of navigating to our next destination, and the cognitive map we build of our environment. Thus, it's important to understand that boundaries do not have to be exclusively physical in nature either. Zacks et. al explains in a series of experiments how our brains actively and passively segment our information streams at points (2001). For example, while watching a movie, certain jump cuts to new scenes could be perceived as boundaries that segment our overall experience in our episodic memory. These event boundaries are key to further understanding why certain people use certain navigational strategies over others.

Just like how our episodic memories are segmented by non-physical boundaries, actual physical boundaries perform a similar function. Radvansky and Copeland (2006) outlines in his series of experiments on how boundaries disrupt our flow of cognition. He had participants carry objects from room to room, but they were made invisible when they were picked of a table in each room. After entering certain rooms, he would ask questions about the previous or currently held object. The results show that the response time was longer when the object was carried across rooms than within the room. Horner, Bisby, Wang, Bogus, & Burgess (2016) performed a similar experiment that questions the role that boundaries had on episodic memory. In their experiment they controlled for other boundary-like factors such as time, distance, and frame of reference, and their results also showed that cross-boundary memory was worse than within boundary.

Thus, it should come as no surprise that boundaries affect the way that we build a cognitive map of our environment. In Mou and Wang (2015)'s research, the observed findings were people can rely either on path integration (dead reckoning) or piloting when it comes to navigating a new environment consisting of boundaries, but the performance was different between these two strategies. Piloting is mapping out an environment by using landmarks, spatial relations between objects, and the geocentric orientation of the environment. Path integration on the other hand is the process of determining the location of something by estimating the traversed distance and direction (Gallistel, 1990). Mou and Wang had participants walk from one room to another room and then tasked them with pointing towards the prompted objects after moving from the learning room to the test room. Those who relied on path integration did not see a significant decay in performance, but those who relied on piloting saw a decay in performance across three variations of the experiment. It should come as no surprise that since our memory of object to object relationships across boundaries suffer, that our reliance on piloting which uses significant landmarks and geocentric orientation suffers as a result. But other mechanisms such as path integration may remain unaffected.

Although, boundaries have been shown to greatly affect the way we traverse our environment and encode relevant information, not much research has been done on manipulating the boundary itself. If we were able to selectively turn boundaries translucent or abstract away their details, how would this change what we already know about boundaries. Would navigation techniques such as path integration and piloting be affected, and how would our episodic memory be affected? Further research into selective boundary manipulation could potentially reveal a lot of questions as to how one can disrupt the separation of what a boundary is and is not. Also, by testing the hypothesis in a realistic environment, we can highlight the practical applications of our research.

The introduction of boundaries in an open environment has shown interesting results in that it would change the frame of reference and the order the objects were encoded (Meilinger et al., 2016). When presented with an open environment, the participant would assume a spatial frame of reference in accordance to the initial starting position. However, those who were placed in boundaries that were oblique to the orientation of the environment it would alter their frame of reference. This experiment focuses on how our spatial map of an environment changes with the introduction of boundaries. However, this does not necessarily hold a light in question to larger more realistic environments such as a shopping mall. If a shopping district is shaped differently can we assume the same patterns would arise in participants? Also, the boundaries presented are invariable and does not let us know any practical applications of such a task.

Gianni, De Zorzi, & Lee, in another experiment closer to the idea posited in our experiment, has tried something similar in their experiment where they tested to see if children could still retain the spatial knowledge after boundaries were made transparent (2018). However, their experiment was only done to show whether children and toddlers were capable of understanding the physical permeance of the barriers. We are more focused on how such a barrier manipulation would affect adults' memory and navigation on a much larger space.

Although there has been manipulations done on other navigational factors in other experiments (such as landmarks (Strickrodt, O'Malley, & Wiener, 2015)), little has been explored in the realm of barrier manipulation in realistic environments. The applications of such an experiment could open a lot of potential as to how we approach teaching navigation in unfamiliar environments.

Methods and Materials

Self-Reported Reported Measurements

In the beginning we start the participants on a couple of surveys to get some data on their self-reported sense of direction and methods of navigation.

Questionnaire on Spatial Representation (QSR) (De Beni, 2001). This first questionnaire reports on the participant's sense of direction and methods of navigation. The two types of navigation that we are focusing our attention to are survey-based and landmark-based navigation (De Beni, 2001).

Santa Barbara Sense of Direction Scale (SBSOD) (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). The second questionnaire measures the participant's self-perceived sense of direction. The results from this questionnaire have been shown to correlate with the participant's actual spatial abilities (Hegarty et al., 2002), and prove to be a useful metric for pre-evaluation.

Psychometric Measures

Advanced Symmetry Span Test (SSPAN) (Alekseichuk, Turi, Amador de Lara, Antal, & Paulus, 2016)**.** The SSPAN was designed to help measure the participant's spatial working memory. For this part we have participants look at a 4x4 grid; the grid will ping a certain number of squares red, and the participants must remember the position and order that the squares appear in. Then they are presented with an empty grid and must try to replicate the order and position that the squares appeared. Interspersed between these pings, is the symmetry task designed to prevent rote rehearsal. In the symmetry task, we encourage participants decide whether a pattern on a grid is symmetrical or not within a given time limit and accuracy level. To stabilize performance, we run the task in 3 blocks.

Training Environment

Practice. For the next few parts, we use a series of virtual environments constructed in Unity on a desktop computer and monitor. We place the participants in a practice virtual environment to have them get used to the control scheme and general layout. The participants are then required to find four out of the five buildings, using WASD to move and the mouse to look around. The program then registers their findings whenever they touch the side of the building.

Wayfinding. Afterwards, we place the participants in a city-like training environment with a total of nine target buildings. A paper of all nine target buildings are given to help the participants keep track, as they find the buildings in any order they wish. Additionally, there are two variations to this environment that the participants are run in.

a. Translucent Realistic

   This environment consists of buildings found in a city-like environment. The participants are also given the ability to see through buildings within their line of sight. The first building in their line of sight is made translucent, and subsequent buildings are removed. The participants can also control the number of buildings they want to see/un-see using the mouse's scroll wheel.

b. Opaque Abstract

Non-target buildings are rendered with a white texture and remain opaque.

c. Opaque Realistic

In opposition to the translucent realistic condition, participants are not able to see through buildings in this variation.

Pointing. After finding three of the nine buildings they are placed into a pointing task; for this part they are given a reference building (one of the found buildings) and must move the cursor in the angle and direction of one of the other found buildings.

The participants are then placed back into the city-like environment to find the other buildings. They must traverse the environment for a minimum of 12 mins, even if they finish early. Once they finish, they are then placed back into the pointing task.

Testing

Proceeding the training task, is the testing task. We run the participants on the Opaque Realistic setting for testing. Also, instead of being able to find the buildings in any order they want, they must follow the order prompted to by the program. After finding all nine buildings they are placed back into a pointing task. Then they must find all nine buildings two more times, with another pointing task in-between. Their responses are recorded and then they are given a post experiment questionnaire asking them about the wayfinding strategies they used to navigate the environment.

Results

Data from the Wayfinding was represented as a percentage error from the optimal shortest path to the next building (calculated by using A* pathfinding algorithm). The performance of the Pointing Tasks was represented as the number of meters away from the store's locations. Thus, for both measurements, the smaller values indicate less error and vice versa. The criteria used to determine high and low SOD and memory capacity were if a participant scored above (high) or below (low) the median (19 and 51.5 respectively).

Overall Performance

The data shows strong evidence of those with a higher memory capacity generally outperforming their counterparts, regardless if abstraction is introduced or not. The ANOVA revealed a significant difference between the Low Memory Capacity group and the High Memory Capacity group in the first block of navigation ($p = .009$) and Pointing testing ($p = .028$). As represented on Figure1, for the Nav 1 and Pointing 1 testing blocks, those with the higher memory capacity outperformed those with a lower capacity.

However, the same can't be said for SOD. Only in the navigation block do those with a high SOD show a significant improvement ($p = .032$) over those with a low SOD (figure 2).

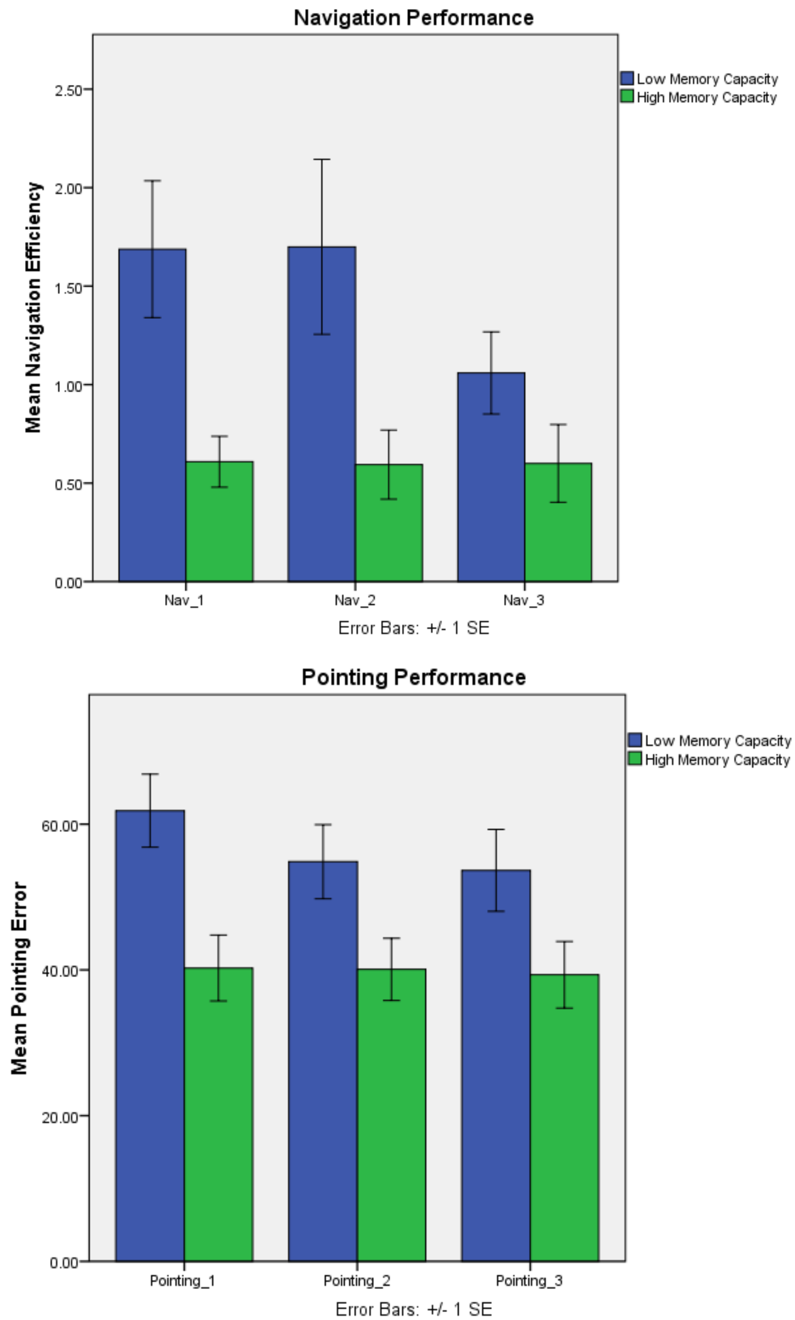

Figure 1. Performance for all three blocks of wayfinding and pointing tasks. The data is on all participants comparing low and high memory capacity.

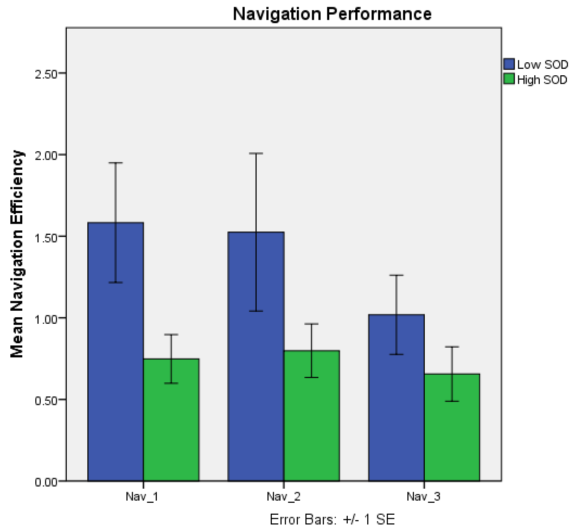

Figure 2. Performance for all three blocks of only the wayfinding task. The data is on all participants comparing low and high SOD.

Differences in Non-Abstract and Abstract groups

The interactions between SOD and each abstract group seem to present conflicting results. The first wayfinding task shows those with a Low SOD perform significantly better (p=.022) in the realistic condition than they do in the abstract case, as shown on figure 3.

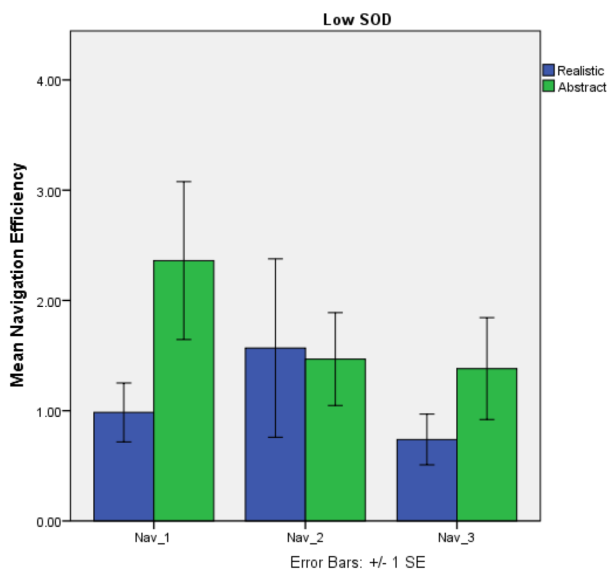

Figure 3. Performance for all three blocks of only the wayfinding task. The data is only on the Low SOD participants comparing the realistic and abstract conditions.

However, in the data in the pointing task show otherwise. Those with a high SOD outperform the low SOD group (p = .002), and this pattern continues for the rest of the trials. In the second (p = .068) and third block (p = .05), those with a high SOD will outperform their counterparts (Figure 4).

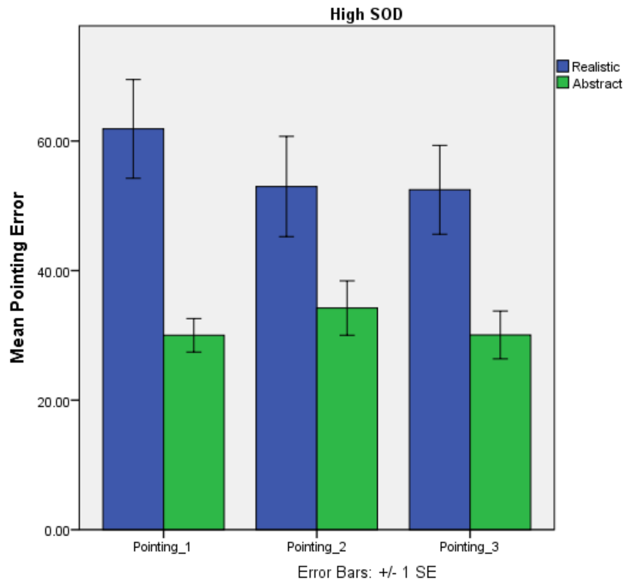

Figure 4. Performance for all three blocks of only the pointing task. The data is only on the High SOD participants comparing the realistic and abstract conditions.

Discussion

The results reveal what methods improve one's navigational ability. In this case, we tested the effects of translucency and abstract boundaries on the participants' overall performances. Success in the testing phase was more reliant on high memory capacity than SOD, with those with a high memory capacity outperforming their counterparts. This should come as no surprise, as those with a high memory capacity are able to retain more information about their environment which they can use to map out the space. However, the significant difference is only really found in the first block for both the pointing and wayfinding trials. The performances begin to converge at a certain level (especially at the third block). This is most likely due to the further practice gained from performing the actual wayfinding blocks.

As for SOD, only in the first wayfinding task did those with a higher SOD outperform their counterparts. This is probably mainly because a high SOD does not necessarily correlate with how well they were able to retain information about their surroundings. For example, one could easily map out their environment given enough time and practice, but when given a short period of time to retain all the information, it could become exponentially harder. And since the testing environment was so large, the cognitive load could be too much to those with a high SOD. The significant difference in performance in the first block could simply be due to participants performing exceptionally well with few storefronts they could remember.

However, even though SOD was not a major significant factor for both the realistic and abstract conditions, there were some interesting interactions between the two. Those with a low SOD in the realistic condition actually outperformed those in the abstract case. This is most likely because those with a low SOD rely more heavily on piloting rather than path integration. When those participants are trained in the abstract condition, it can be harder to establish a frame of reference, which they use to construct a map of their surroundings. Then when they are suddenly placed into the testing phase (the opaque realistic condition), the associations they did make in the training phase are harder to translate in the new context. As show in the data, this most likely gets better in the following blocks because participants can relearn the map and establish new frames of reference.

In the pointing task, the opposite is true. Those with a higher SOD display less pointing error in the abstract conditions. This aligns quite well with establish research and the interpretation of memory capacity and SOD. Many individuals with a high SOD use path integration, which only requires direction and distance travelled to determine locations. So, it may seem that those with a high SOD should be able to pinpoint the location of objects more accurately; however, as previously mentioned, without a high enough memory capacity, the extent to which these high SOD participants can perform is most likely limited to how much information they can retain. Thus, having a lower cognitive load in abstract condition greatly ameliorates this issue. By stripping information of the surrounding buildings and having a direct line of sight to each target building, high SOD individuals can easily outperform those in the realistic condition in the pointing task.

Conclusion

The results of this experiment show interesting interactions between translucency and abstraction. If one has a high enough memory capacity, having either transparency or abstraction doesn't improve performance. And if one has low SOD, they definitely should not attempt to use translucent abstract boundaries to try and improve performance. However, those with a high SOD will see improvement with this translucent abstraction tool.

Such data provides an interesting and practical viewpoint on how boundary manipulation can affect one's navigational abilities, and how the results align with current theory.

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Appendix

SBSOD (Hegarty et al., 2002)

Sex: F M
Age:_______

Today's Date:______________
V. 2

This questionnaire consists of several statements about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle "1" if you strongly agree that the statement applies to you, "7" if you strongly disagree, or some number in between if your agreement is intermediate. Circle "4" if you neither agree nor disagree.

1. I am very good at giving directions.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I have a poor memory for where I left things.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I am very good at judging distances.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

4. My "sense of direction" is very good.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).

   strongly agree 1 2 3 4 5 6 7 strongly disagree

6. I very easily get lost in a new city.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I enjoy reading maps.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

8. I have trouble understanding directions.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

9. I am very good at reading maps.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

10. I don't remember routes very well while riding as a passenger in a car.

    strongly agree 1 2 3 4 5 6 7 strongly disagree

11. I don't enjoy giving directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

12. It's not important to me to know where I am.

strongly agree 1 2 3 4 5 6 7 strongly disagree

13. I usually let someone else do the navigational planning for long trips.

strongly agree 1 2 3 4 5 6 7 strongly disagree

14. I can usually remember a new route after I have traveled it only once.

strongly agree 1 2 3 4 5 6 7 strongly disagree

15. I don't have a very good "mental map" of my environment.

strongly agree 1 2 3 4 5 6 7 strongly disagree

QSR

Questionnaire on Spatial Representation (Pazzaglia et al., 2000)

1. Do you think you have a good sense of direction?
   1 (not at all) 2 3 4 5 (very good)

2. Are you considered by your family or friends to have a good sense of direction?
   1 (not at all) 2 3 4 5 (very much)

3. Think about the way you orient yourself in different environments around you. Would you describe yourself as a person:
   a. who orients him/herself by remembering routes connecting one place to another?
      1 (not at all) 2 3 4 5 (very much)
   b. who orients him/herself by looking for well-known landmarks?
      1 (not at all) 2 3 4 5 (very much)
   c. who tries to create a mental map of the environment?
      1 (not at all) 2 3 4 5 (very much)

4. Think of an unfamiliar city. Write the name ....
   Now try to classify your representation of the city:
   a. survey representation, that is a map-like representation
      1 (not at all) 2 3 4 5 (very much)
   b. route representation, based on memorising routes
      1 (not at all) 2 3 4 5 (very much)
   c. landmark-centred representation, based on memorising single salient landmarks (such as monuments, buildings, crossroads, etc.)
      1 (not at all) 2 3 4 5 (very much)

5. When you are in a natural, open environment (mountains, seaside, country) do you naturally individuate cardinal points, that is where north, south, east, and west are?
   1 (not at all) 2 3 4 5 (very much)

6. When you are in your city do you naturally individuate cardinal points, that is do you find easily where north, south, east, and west are?
   1 (not at all) 2 3 4 5 (very much)

7. Someone is describing for you the route to reach an unfamiliar place. Do you prefer:
   a. to make an image of the route?
      1 (not at all) 2 3 4 5 (very much)
   b. to remember the description verbally?
      1 (not at all) 2 3 4 5 (very much)

8. In a complex building (store, museum) do you think spontaneously and easily about your direction in relation to the general structure of the building and the external environment?
   1 (not at all) 2 3 4 5 (very much)

9. When you are inside a building can you easily visualise what there is outside the building in the direction you are looking?
   1 (not at all) 2 3 4 5 (very much)

10. When you are in an open space and you are required to indicate a compass direction (north-south-east-west), do you:
    a. point immediately?
    b. need to think before pointing?
    c. have difficulty?

11. You are in a complex building (many floors, stairs, corridors) and you have to indicate where the entrance is, do you:
    a. point immediately?
    b. need to think before pointing?
    c. have difficulty?

Post Questionnaire

1. How helpful the concaved corner was in the wayfinding task?

    1 (not helpful at all) 2 3 4 5 (very helpful)

2. How helpful the concaved corner was in the pointing task?

    1 (not helpful at all) 2 3 4 5 (very helpful)

3. How helpful the enclosure was in the wayfinding task?

    1 (not helpful at all) 2 3 4 5 (very helpful)

4. How helpful the enclosure was in the pointing task?

    1 (not helpful at all) 2 3 4 5 (very helpful)