Thinking with Portals: Exploring the development of cognitive maps in non-Euclidean space

Background

As early as when a child learns to crawl, navigation, the ability to identify one's position and follow a route through space, becomes a necessary part of life. For example, one has to be able to identify their mother or father in a room and crawl toward them across a floor potentially littered with obstacles such as chairs, toys, and even pets or other people. Beyond just reaching a target in sight, navigation involves planning how one will go between rooms to reach the target using information about the placement of doors and the connectivity between rooms. In order to navigate these spaces, it's clear that children and adults must have some internal spatial representation they use to inform the path they take.

Recent research has worked to show the nature and robustness of the representations in children of real locales and how they develop into adulthood. Starting from the most basic understanding of space, we know that the humans build that representation egocentrically rather than geocentrically. Namely, they choose to only include information in their space that supports how they choose to use the space relative to their own needs (Wang & Spelke 2002). This suggests that at some level of visual processing, humans distill the complex and abundant visual information into some abstract minimal set of information that still retains its original form (Siegel & White 1975). Indeed, this is what is observed when humans are then asked to verbalize their representation. In Kevin Lynch's seminal paper on urban planning, he asks adults living in the cities of Boston, Jersey City, and Los Angeles how they navigate the complex urban environment. He organizes their ideas into 5 distinct concepts describing space: edges that describe the boundary of a space, nodes that represent locations of interest, paths that connect nodes together accessibly, districts that contain nodes of similar use, and landmarks that anchor the space and aid in navigation (Lynch 2020). It's worth note here that not all the information about a location is captured in this representation. Not only that, but the quality of the information changes over time and our representation is transient and will fade quickly without repeated exposure.

Given that we know that repeated exposure is necessary in transferring a spatial representation from working memory to long-term memory, a natural question that arises is what information is processed, in what order, and how does that process differ between children and adults and between different adults. In a study, scientists investigated the visual versus practical information encoded in space. They made several spaces that looked radically different but were fundamentally the same and told children to calculate the distance between objects within these spaces. They found that if one can give examples of the similarities between the spaces, the children can from common relational schemas between them to accurately identify the distances (Loewenstein & Gentner 2001). However, another study found that this ability to form relational schemas and orient oneself in a space is limited in children. Namely, adults are able to use both geometric and non-geometric cues in a space whereas children can only robustly use geometric cues to form schemas (Hermer & Spelke 1994). Despite this limitation, children attain adult-level representation as early as level 12 (Nazareth et al. 2018). However, it is also known through research that adults fall into three categories based on their ability to understand and navigate a space: imprecise navigators who form imprecise ideas of routes, non-integrators who represent routes accurately but are imprecise in relating two routes, and integrators who relate routes and thus form robust cognitive maps (Weisberg & Newcombe 2016).

In another vein, in understanding how people represent space it is useful to investigate how children build the representations if they face some disability that would inhibit their ability to form them. In one study investigating students with dyslexia, they found that in their representations they formed preferences for direction and had different representational accuracy depending on how they chose to explore a space (Vieira et al. 2013). Interestingly another study found that the representation of space in blind children does not deviate far in accuracy from sighted children and do much better than children with dyslexia (Fletcher 1980). However, what remains true in both cases and in children as early as 3 is that children can achieve the converse with ease: they can go from a physical model or representation of space to navigating the real thing with little training (Blades & Cooke 1994).

Despite all the progress that has been made in the past few decades to understand these representations of space, there are still many questions that remain about their true nature. Specifically, although there is a lot of information about how visual information and experience is used to build the mental representation, little is known about how those representations might fail to capture everything about a space. This failure might happen in two ways: the representation has difficulty adapting to a changing environment. The world is always moving and changing and so are the environments we explore; a representation fails if it cannot account for that fact and update itself as one receives information. The other way the representation might fail, and the way we choose to investigate in our study, is if that representation is too reliant on underlying assumptions about the world or the environment where the representation is made. A good example of this is a person who lives in a major city and commutes to work every day on the subway. They know how to navigate to the nearest subway station and use the system to its fullest. However, if one day for some reason the entire system is offline, suddenly they have to resort to using a map to navigate because their understanding of the space was distilled to only places accessible by and not made unnecessary by the subway system.

Another true yet more esoteric failure in the representation of space are fundamental assumptions about geometry: Humans assume that space is Euclidean—that it satisfies basic geometric principles. Some examples are the Pythagorean Theorem, the sum of the interior angles of a triangle being 180, and the intuitive fact that taking 3 left turns after traveling the same distance in between will leave you back where you started. These assumptions are of course true, but only locally. A commonplace example of when this are flight paths; many people often get confused when they see that the optimal flight paths on international flights are curved instead of a straight line between the two airports. This is because curvature of the Earth on these long flights actually introduces non-Euclidean geometry into the representation; the 'curved' lines are in fact geodesics—straight lines around the Earth.

In this study, we tackle the assumptions in Euclidean geometry concerning the connectivity of space. An example of this is the intuitive notion that if I pass through a doorway on the wall of room that I have left the room. However, in non-Euclidean geometry it's entirely possible to simultaneously enter and exit a room through the same doorway. This leads to the idea of portals: a doorway that connects two formerly distinct points in space. We use this idea of portals to test the robustness of our spatial representation. Specifically, can we adapt our understanding of space to accommodate for portals that would otherwise violate our senses and can we still navigate this space with non-Euclidean connectivity. By trying to get our participants to do so, we hope to glean information about how we form our mental representations and how might they fare when given various unknown situations with a self-consistent set of rules inconsistent with normal reality.

Experimental Setup

Children's understanding of the world develops over time and which rules are innate vs learned. For instance, children understand that continuity and solidity are innate features of the physical world. However, building an understanding of gravity and inertia takes time to develop. In our proposed experiment we will investigate the idea of continuity, particularly in relation to navigation and representations of space.

In navigation we make many assumptions about the surrounding world. Namely, we assume that space is locally Euclidean. This leads to conclusions such as: If an individual walks out of a room through a doorway, they are no longer in the room; if an individual leaves through the doorway and I follow, the individual will be waiting on the other side; lastly, if an individual walks away from me at a constant velocity, then the distance between us increases linearly. In our proposed experiment, we intend to subvert these assumptions and observe the development of three things in children over time: How quickly can children update their representation of space, what is the nature of the representations the children create, and how robust are these representations to change and ambiguity in the rules governing the space. Lastly, we hope to compare these findings with the findings from conducting the same experiment on adults to see the similarities and differences in the systematic errors they make.

For the experiment, we will collect data from two different groups: a representative sample of children ages 4-12 and a representative sample of adults aged 18-25. We place each child in a VR room simulation. In this VR space, the child is put in the middle of a square room. We have generated four experiments of increasing difficulty that test the children's and the adults' abilities to form a logical map of the space:

- **Experiment 1:** In the box will be two 'vents' placed on opposite sides of the room. Each vent is lined with a single color: orange in contrast to the gray walls of the room. Nothing is visible through the vent. A ball is then passed through the vent by an experimenter also in the simulation. The vent is then programmed to teleport the ball to the vent on the other side of the room with the same momentum such that it exits the opposite vent collides with the participant in the center from behind. This gives the impression of a 'portal'. Several iterations of this experiment are done, with the ball being rolled into each vent and exiting the other, to show the connectivity of the two vents. The behavior of the participant is then noted and recorded. How does their gaze change as you go through the iterations? Can they predict where the ball will be after entering the vent?
- **Experiment 2:** Experiment 2 is very similar to experiment 1 except that rather than placing the vents on opposite sides of the room, the two vents are placed on any two of the four walls. Factoring in rotational symmetry, there are 3 ways to choose vent placements. Do they still anticipate the ball will exit the other vent independent of the wall?
- **Experiment 3:** Now that we've introduced the participant to the concept of portals, we add two more vents to the rooms on the unoccupied walls. These vents are lined with a color distinct from the other two vents: green. Now, when the experimenter is demonstrating how the vents work, they will roll a ball into one vent and the simulation is programmed to deposit the ball with equal momentum out the vent of the same color. For instance, if the ball enters an orange vent, it will exit the other orange vent; if it enters the green vent, it will exit the other

green vent. This time we choose to also include all the arrangements of the vents, of which there are 2.

- **Experiment 4:** Experiment 4 introduces the most change of the experiments. As in experiment 3, there are 4 vents, one on each side of the room. However, instead of them being line with two pairs of the same colors, they each have a unique color of orange, green, yellow, and red. Factoring in rotational symmetry, there are 6 ways to arrange them. The connectivity of the vents is as follows: orange -> red -> yellow -> green -> orange. This means that rolling a ball into the orange vent means it will exit the red vent, into the red vent will exit the yellow vent, and so on.

Throughout this, our observed variable is measuring if and where the child expects the ball to return the area based on what vent it entered. For example, they might turn around if they expect the ball to collide with them from the back after watching the ball enter the front vent; or they might reject the idea of portals altogether and keep examining the vent for tricks. From this we hope to gain insight into how quickly the child can learn the new paradigm of the vents and how complicated the vent setup can be before the child becomes confused and expects different exit vents with different probabilities. The main point is that the connectivity in a single setup is always logically consistent. Thus, we can learn more about how children learn about these rules of navigation under a new paradigm different from the natural world.

Discussion

As the participant progresses through the various experiments we've devised, we hope that the participant will attempt to form a cognitive map of the room with considerations of the connectivity of the vents. It is this cognitive map that we attempt to break through gradually increasing the difficulty of the map by changing the connectivity of the vents. By observing how the participant reacts to the movement of the ball and anticipates where it will exit and identifying systematic errors in how they represent the space based on those observations, we hope to glean how these representations are structured in the brain and how robust they are. For each experiment, we have made a hypothesis as to how the participant will react and what errors will be observed regularly, if any.

For experiment 1, we hypothesize that almost all of the participants will quickly recognize that the two vents are connected and that this connection is robust on the specific colors used (or even no colors at all). They will eventually see the ball roll into one vent and turn around to observe the ball coming out of the other vent.

For experiment 2, we hypothesize that the majority of the participants will still expect the ball to exit from the other vent. However, the youngest participants—those close to 4 years of age—will still expect the ball to come from the opposite wall rather than from the other vent which might not be on the opposite wall. This is because they've simply recognized the path of the ball and formed the association that the ball will always appear behind them.

For experiment 3, we predict that the adults and older children will continue to be able to form the correct representation of the connectivity between the vents. Also, some of the younger children who had difficulty with experiment 2 will actually be able to accurately form the representation when the pairs of vents are placed on opposite walls. This is because with this configuration they can still form the association that the ball will come from the opposite side as opposed to needing to understand the underlying connection between the vents.

For experiment 4, unlike the other 3, we predict a high rate of error in predicting how the ball will move between portals and a very long time to form the consistent representation, even in the adults. This is because of several factors: This experiment violates a key association that had been established in the other experiments, that the ball would always exit the other vent of the same color as the one it entered. However, here, there are no vents of matching colors. The participants now have to reformulate the association between vents as a directed network of connectivity rather than sets of paired vents. This different type of network would require a lot of Bayesian inference and many trials to construct the consistent framework that underlies the network of vents. Although there is evidence that shows that children can perform Bayesian inference to some degree, the level necessary would likely be much higher than they would implicitly understand and require structured thought, for example by taking notes after the repeated trials and the input and output vents.

General Discussion

The formation of spatial representations and spatial maps of a location is a critical part of navigation and memory in humans. However, in most real-world scenarios, the locations that we map are limited to non-Euclidean geometries In this study, we devised a way to challenge the participants' ability to form these representations in a non-Euclidean space in the hopes of understanding their accuracy and robustness as a function of the complexity of the space.

Through the series of experiments that pose progressively more difficult scenarios for spatial representation formation, we answer several questions: Can humans form a structured representation when presented with non-Euclidean features in the space (in our case the portals)? Are these representations robust under a change in the position of the portals by creating an underlying schema or is the representation simply an association between location of the event and association between colors, which could be considered landmarks of the space? Lastly, we answer the question of whether or not the participants can update their representation to account for new information or a change in the spatial paradigm (i.e., can they adapt to a change in how the portals are connected and what the colors mean for connectivity)? With this study, we hope to answer these questions and gain a more fundamental understanding of the formation of spatial representations in humans.

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