Project 2: Visual Cues and Planning Strategies during Indoor Navigation

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Team Name: Take Me To Your Leader

1 Introduction

Developing a computer agent that models human cognition is a demanding undertaking, especially in the realm of spatial navigation. Humans have a remarkable ability to understand, remember, and learn from a space they navigate often. Even in completely new spaces, humans are able to explore and find a target with little trouble.

However, understanding the processes involved in how humans navigate both new and familiar spaces has applications in many fields, specifically in computer way-finding systems [1, 2]. With new products coming on the market such as package delivery systems or warehouse automated guided vehicles, the ability for a computer agent to navigate an unknown space, learn from that space, and improve performance over time is quite important to modern technological needs. This study aimed to investigate how humans are able to navigate unfamiliar spaces, learn from each attempt, and improve over time. It then aimed to build a computer agent who implements or mimics those cognitive elements in similar environments.

Previous studies have investigated both human and mammal brains and behaviors [3–5] to understand cognitive mechanisms of human spatial navigation. A wealth of studies reported involvement of the hippocampus in spatial-navigating tasks, showing memory takes a large role in this cognitive process [4,6,7], still others [8,9] say both allocentric (global map), egocentric (relativistic locations), and beacon-oriented navigational understanding of one's location are critical factor for successful way-finding. Some views [3, 10] assert that navigation agents might produce cognitive maps when they explore a space, which emphasized the imagistic reasoning in spatial navigation. Meanwhile, Vukovic [11] supposed the importance of language in a spatial navigation system and supports the sentential reasoning aspect of the cognitive mechanism.

Likewise, this seemingly simple way-finding task requires implementation of many different cognitive functions. As alluded to previously, the current study aims to expand understanding of the human cognition process of spatial navigation. The team built on previous class work that was done in navigating completely unknown spaces using only a rules based approach. In the previous work, the team developed a cognitive agent that could learn and improve on its navigation using the complete set of cognitive tools available to a human navigator. In this project, the team took a step further and implemented other cognitive aspects of the human navigator to the cognitive agent. Specifically, the team tasked itself with building an agent that can find a target office in an office building. Through multiple trials, the agent should learn and improve upon its path, utilize rules-based reasoning, imagistic reasoning, anchoring, and emotion-based reasoning similar to that used by a human agent in the process.

Starting this project, the team's hypothesis was that participants would initially use rules-based approaches based on room numbers (a hypothesis pulled from previous work). Once a participant has gone through the map once, the team hypothesized that participants would develop cognitive maps of the area and navigate using those maps. When the team found that participants were actually using images and imagistic reasoning for navigation, the team hypothesized that participants were using anchor images to form an activation network that associates the anchors with necessary movements - a hypothesis tested in a second round of interviews as discussed below.

2 Method of Study

The study was conducted using participant interviews. A virtual environment was developed that enabled users to navigate a completely unknown space, and also allowed researchers to modify that space as needed to investigate specific cognitive processes used (See 'Virtual environment' for the details). Both post-hoc and speak-aloud interviews were used as described below. To identify various cognitive tools, the study implemented three sets of experiments, where slightly different environments were tested. The main task for participants was finding a target location (i.e., a specific room number).

2.1 Participants

The team formally interviewed 17 participants (8 Females; Age range = 20-36) for this study. The study utilized with three sets of experiment, where seven participants (3 Females; P1-7) were recruited for the first set, 4 participants (3 Females; P8-11) were tested with the second set, and the rest 6 participants (2 Females; P12-17). Among all participants, 12 participants were graduate students at the Georgia Institute of Technology, 3 were college graduate (Non-GT) education professionals, 1 was a college graduate (Non-GT) business professional, and 1 was a college (Non-GT) undergraduate student.

The team tested two maps in the third set of interviews, one with a large map and the other with a small map. Data collected from the two maps were used to test the performance of the agent against human way-finders. Especially, the data collected from the small map was used only for validating the simulator we created, so was used sparingly in the analysis. Meanwhile we will discuss the analysis results from the large map further below.

2.2 Virtual environment

The team used the Processing development tool (Processing.org) to generate 3-dimensional virtual environment. Participants could interact and navigate the space with four direction keys. The space basically had gray walls and brown doors, and there was only one entrance point. The outside of the navigation space was indicated with endless grass. The space was purposely simplified to avoid possible confounding factors. As participants went through the environment, screenshots, agent location, orientation, and time were recorded for later analysis.

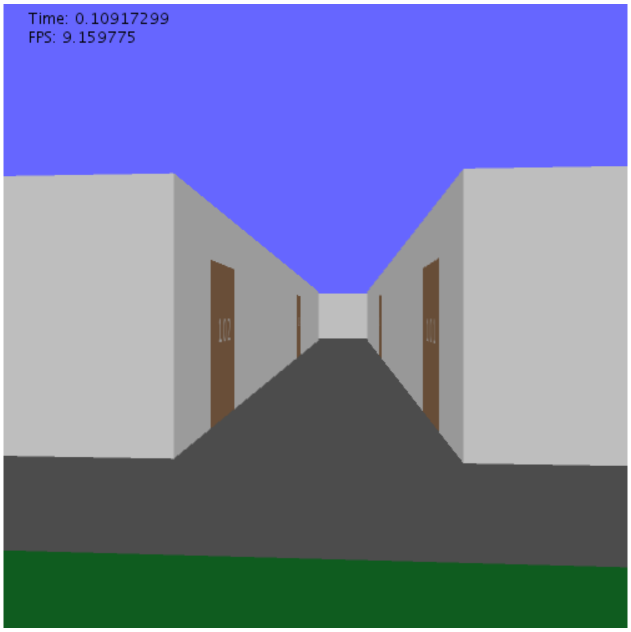


Figure 1: An example image of the virtual environment

2.3 Protocol

The protocol varied based on what the team was looking to identify. An initial set of interviews were conducted to collect preliminary information on how participants navigate the space over multiple trials. Once data was collected and analyzed, a second set of interviews were conducted to narrow in on how participants used anchor objects in navigation. Finally, a third study set was conducted, to probe how confusion and confidence affects participants in navigating a space. The small map in the third set was primarily used to to test the agent once developed. These interview sets are described separately below.

Trials were run multiple times in order to identify the cognitive methods that human subjects use to learn a path over time. Between each trial, interviews were conducted with participants to identify the the specific cognitive mechanisms (e.g., rules, images, analogies, emotions, etc) used to find the target.

2.3.1 Set 1

The first set of experiments aimed to investigate how people navigate and find a target location. The virtual space had door numbers and several objects on the hallway, simulating a simplified version of real office floor environment. The objects used in this set were two different file cabinets, a trash bin, and a table. The objects were placed at different locations (randomly) each time the program was run, while door numbers were fixed. A detailed process of the interview is described below:

1. Ensure participants spawn at the entrance to the building
2. With all room numbers in place, ask participants to find room 126

3. Once found, ask participants to return to the starting location
4. Ask participants what their approach to room finding was and how the participant chose actions at each decision point (intersecting hallways)
5. If able, ask participants to draw a map of the area and their path.
6. Repeat 2-5
7. Remove room numbers except room 126 and repeat 2-5
8. With room numbers in place, repeat 3-5 asking participants to find room 114
9. Remove room numbers except room 114 and repeat 3-5

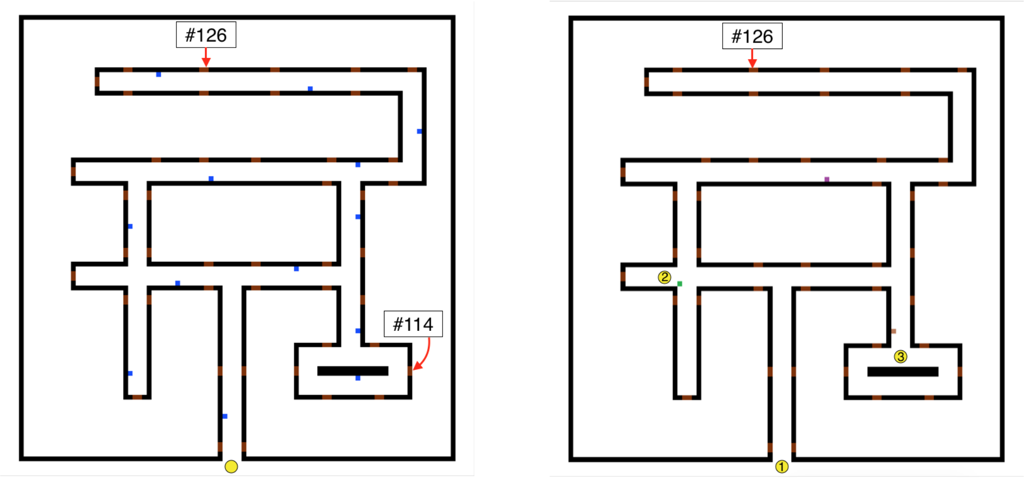


Figure 2: Maps used for the experiments. Wall was indicated with black line and doors were displayed at dark brown colored points. Spawn locations are denoted with yellow dots. *Left*: Map used in the experiment Set 1. Blue dots indicate locations of random objects. *Right*: Map used in the experiment Set 2. Different colored dots indicate locations where different objects displayed. Purple: table, green: plant, and light brown: basket. Numbers in yellow dots indicating the order of spawn locations. For participants tested without objects in the map, we removed the three colored dots and presented the map that only has walls and doors.

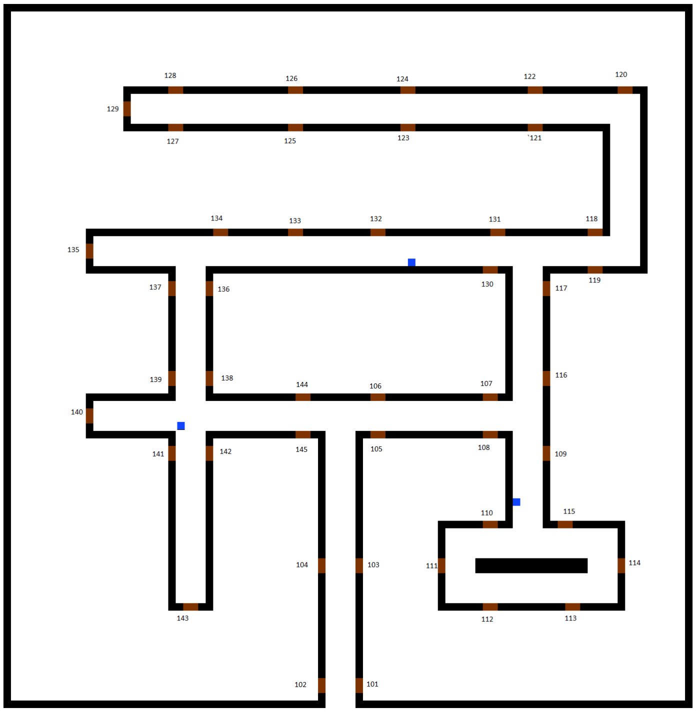


Figure 3: Floorplan with room numbers.

2.3.2 Set 2

In the Set 1 experiment, the team observed participants were highly dependent on the door numbers during the initial exploration. To investigate other cognitive methods humans implement for spatial navigation, the team decided to test a few separate participants using a different method. In the map used in Set 2 experiment, the doors did not have number labels except for the target door (during the entire experiment). Also, two participants (P8 and P9) went through a map where objects were displayed. Here, rather than displaying objects at several points randomly, there were three fixed object locations. The objects used in this set were a basket, a table, and a plant. In addition, the other two participants were tested with no objects (P10 and P11) to test the effect of objects. Only walls and doors without number labels were displayed. The procedure of Set 2 was like below:

1. Ensure participants spawn at the entrance to the building
2. Without any room numbers (except room 126), ask participants to find room 126
3. Once found, ask participants to return to the building entrance
4. Ask participants what their approach to room finding was and how the participant chose actions at each decision point (intersecting hallways)
5. Repeat 2-5
6. Change the spawn location to ”spawn location 2”

7. Repeat 2-5
8. Change the spawn location to ”spawn location 3”
9. Repeat 2-5

2.3.3 Set 3

A final set of interviews with the large map were conducted primarily to investigate how emotional factor (i.e., confusion and confidence) affects human spacial-navigation performances. To achieve this, 6 participants (P12-17) navigated a large virtual space and were asked to find a target door. The team repeated the same procedure to the same participants with the small map. As mentioned above, the data collected from the small map was used only for testing the performance of the computer agent we developed. Thus, the discussion for the small map was not dealt heavily in the data analysis section, but the team more focused on analyzing the data from the large map. The third interview set was more informal. Participants were asked to think aloud while navigating the spaces, and interviewers asked few pointed questions regarding their cognitive processes. The procedure for Set 3 was as follows:

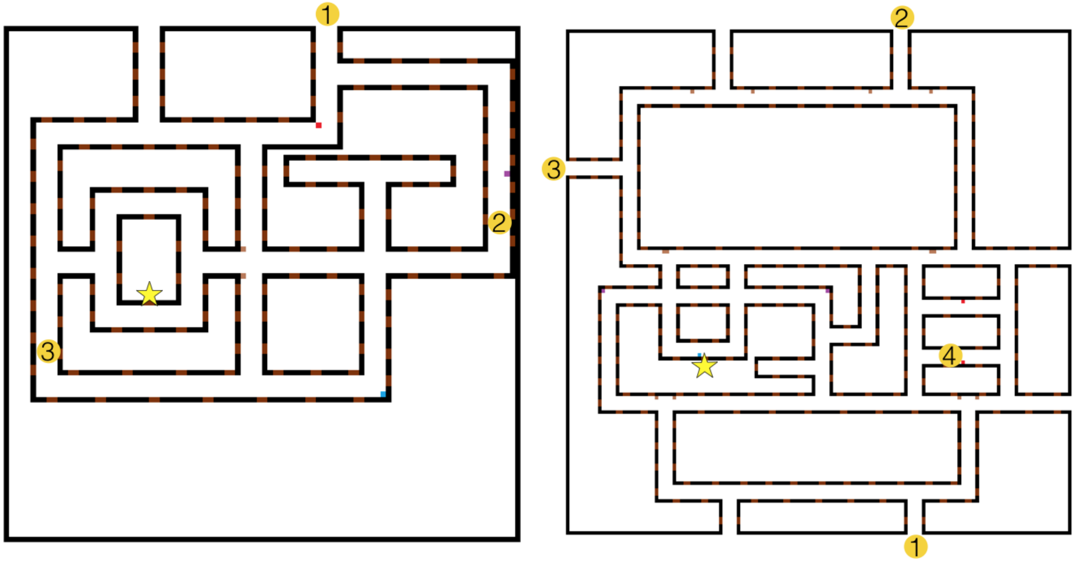


Figure 4: Large map used for interview Set 3. Different spawn locations are indicated with numbers in yellow circles. Target point is marked as a star. Light brown color is location of chairs, red is plants, purple is tables, and blue is trash can. *Left* Small map. *Right* Large map

1. On the small map, set participant to ”spawn location 1”
2. Ask participants to find the room with ”ME!” on the door. Ask participants to think out-loud, noting the reasons for actions, feelings, thoughts, notable figures etc.
3. repeat step 2 on the small map using ”spawn location 1”
4. repeat step 2 on the small map using ”spawn location 2”

5. repeat step 2 on the small map using ”spawn location 3”
6. repeat step 2 on the large map using ”spawn location 1”
7. repeat step 2 on the large map using ”spawn location 1”
8. repeat step 2 on the large map using ”spawn location 2”
9. repeat step 2 on the large map using ”spawn location 3”
10. repeat step 2 on the large map using ”spawn location 4”

3 Data Collected & Analysis

The data collected was broadly broken up into 2 main categories. First, there was the initial way-finding interview segments, in which the participants were new to the area and had to figure out their path for the first time. Second, there was data collected during the repeat segments, in which participants were going back to an area that they have already seen. The data collected is split between these two categories and analyzed as applicable in-line below. As discussed previously, the findings discussed here were mainly from interview Sets 1, 2 and data from the large map navigation interview of Set 3.

3.1 Initial Way-finding

The data collected and results from this processes were different between the first experimental set and second experimental set described in the protocol section above. As such, this data is further split below:

3.1.1 Set 1: Room Numbers Available to Participants

Initially, participants tended to rely on rules to find the room. If room numbers were available, they almost always used room numbers to get closer to the target room location.

A selection of interview notes and quotes are provided below:

> P3: She Looked at room numbers, and tried to find a pattern to the numbers. Initially she looked at evens/odds to see which side of the hall the room would be on, but then saw that there was a turn. She saw rooms 108 and 144. Initially she tried to think about which number was closer to 126, but noticed the direction of 144 was increasing in numbers, so turned toward 108 instead. After turning toward 108, at each decision point she looked to see which numbers were increasing and followed those to room 126.
>
> P2: The interviewee first navigated the map with numbers on the doors. He pretty easily found the room 126, where he said he was referring to the numbers on the doors to find the room. When he was asked to explain how he found the room, he was confused and said that he turned left at the very first junction while he actually turned right.
>
> P3: ”After [turning toward room 108] I just looked to see which rooms led me to 126. Like I turned and saw 115 and 118, so I went toward 118 because that was closer”

> P5: "I started looking at the numbers and saw they were going up. I saw 144 and thought that was way too high, so I went in the opposite direction."
>
> P7: "At the first junction, I saw two door numbers and made a turn that I thought closer to 126."

As also found in the earlier class research, this data further supports the hypothesis that participants tend to use rules-based approaches when investigating a previously unknown area. Since participants have no knowledge of the area, they appear to use the tools available to them to navigate the area. In the previous examples, the most recognizable or useful tools to participants appeared to be room numbers.

Of further interest, while still relying on rules, some participants appeared to use analogies and case based reasoning (CBR) when asked how they approached the problem:

> P5: "This reminded me of trying to find [a friend's] apartment [in their apartment building]".
>
> P10: I did the same exact thing I do in hotels. By saying to me, go find room 126, the first thing I that popped into my head was a hotel room. There, every time you leave the elevator, everything looks the same, so you naturally need to keep track of where you've been.
>
> P6: "I realized the second horizontal hallway was linked to the first horizontal hallway from my previous experiences of navigating buildings. I mean, I thought it would be make sense that those hallways are connected."

This approach (using analogies and CBR) may help them determine which rules need to be applied. For example, if a participant knows that in a hotel hallway, they follow the trajectory of the numbers (increasing/decreasing), they assume they can apply the same rules in this situation.

In particular, this could have lead to the confusion of participant 5 (discussed in detail later), where she said:

> P5: "I got confused because the numbers seemed to jump unexpectedly".

Perhaps confusing her since she expected the numbers to flow more naturally as they may in a hotel/simple apartment.

3.1.2 Set 2: Room Numbers Unavailable to Participants

If room numbers were not available, participants tended to randomly search for the room, keeping a relative mental tally of which areas have been searched and which were not searched:

> P8: "I tried to remember the objects so that I could notice the area I went."
>
> P10: "This reminded me of a video game. I knew I needed to get my bearings, so I just started looking around and tried not to make a circle or go somewhere I've already been"
>
> P11: "Initially, I kept made right turns so that I could make sure where I searched already and not."

These results are particularly interesting since none of the participants (in either set of experiments) showed an ability to redraw a map of the area. This indicates that while they may remember relative location (ex. This hallway is left of the hallway I was just on), they don't create a cognitive map or know exactly where they are in the space relative to their starting positions.

3.1.3 Set 3: Large Space without Room Numbers

In the large map, where the room numbers were not available, participants started randomly navigating the space in the initial wayfinding.

> P15: "I'm just wandering around this space. There's no room number and this space is so large, so I cannot remember the path I went."
>
> P16: (When asked how do you think you found the target door) "Just... by chance?"

During the navigation, participants frequently said they were confused.

> P13: "I think I've been here. Wait, have I been here?"
>
> P15: "These chairs are here and there, and it made me confused."
>
> P18: "I feel lost. ... I'm even not sure whether that entrance is where I started."

While their choice of taking paths didn't really have rules or reasons in the very beginning, as time went by, they realized some objects and used them for deciding which way to go.

> P14: "Oh those pots[plants] again! I remember that I've already been there." P16: (When asked why did you take the right turn) "Because I took the other way before, when I saw that table."

3.2 Repeat Wayfinding

After participants had been through the map at least once, their methods of wayfinding tended to change. They focused less on rules-based approaches and more on imagistic reasoning to identify locations from memory and an emotional toolset to help make decisions in uncertain situations. Since these were the overarching groupings of the data, this data will be presented and analyzed in the context of those groups. A selection of interview notes and quotes are provided below.

3.2.1 Imagistic Recall

All of the participants described using "memory" to determine the necessary route. Specifically, all participants described a visual memory, seeing a picture that reminded them of previous actions.

> P2: "This door [room 120] worked me as a mark before I arrived to the target door, because the view of the room is quite distinguishable from the others."
>
> P5: I remembered the turns I needed to take [to get back to the starting point]. In my head ... I was seeing where I needed to go.

> P5: I didnt remember a map of the area specifically, but I saw room 108 and knew I needed to turn left to get [to the starting point].
>
> P7: "I could realize that I was in a wrong alley, because, I don't know, the view gave me a different impression. Maybe it is longer than the other?"

Participants all indicated that as they repeated the trials, they stopped looking at the numbers (progressively more in subsequent trials) for direction and instead started looking at them as reference or anchor points. As discussed, while participants commonly said "I just remembered which way to turn", when probed about what exactly they remembered, they often indicated it was a visual object - a number, a door placement, an object in the hallway - which triggered the memory of an associated action (ex. turn left) with that object. These objects appeared to be anchor points, or specific features that are stored in the participants memory that activate other concepts, actions, or rules.

This idea of image stimulated activation networks follows Anderson's ACT-R theories [12] and provides a reasonable framework for image-based memory observed in the subjects. Additionally, the ideas of visual landmark identification [13] and using beacons for periodic navigation [9] is supported in literature. Along this same logic path, there is support for the claim [4, 14] that this type of egocentric visuo-spatial navigation dominates and the allocentric (fixed global map) navigation model is not observed.

Further, even when the actual door numbers were removed, participants still said they could visualize these anchors:

> P3: I was just visualizing what the doors said in the previous [trials].
>
> P5: 144 should have been on that [door] to tell me to go right.

While emphasizing the point that participants tend to use visual cues to help with navigation, this particular phenomenon appears to be more sequential behavior. Participants can visualize a route, and know where the anchor objects should be along that route, but may not be able to identify those same "non-existing" anchors if they came about them at a different point in time. These suspicions were supported in trials in which the participant approached the anchor points from a different direction or the spawn location was changed. Without the markers in place, participants had trouble getting their bearings. However, once the participants did figure out their location (ex. by finding the outside area), they again knew where their "unknown" (non-existent but visualized) markers should be.

These ideas (use of anchor points and orientation in space, egocentric localization model) were further investigated in the second set of experiments. The results confirm the importance of anchor objects as reference points along a path, though bring to up interesting conclusions about how humans develop anchor points (discussed below).

> P9: I remembered I passed this table, so I knew I needed to keep going straight. I had to turn left and I saw the fire [plant object]. I remembered I never passed the fire [but I walked by it], so I knew I needed to turn left at the fire.
>
> P11: I realized I went the wrong way [from the previous trial] when I saw that box [the trash can] But then I saw the table and I realized it must have made a circle. So I knew I passed the table on my right, so I turned around [to have the table on my right] and could just keep going as if I had gone the right way.

These objects appear to help both with activating navigational memories and with orienting the participant in the map if they were spawned at an unknown location. They were able to use them as anchor points with which to activate necessary turn sequences (often stimulated visually as discussed above). This relationship between anchor objects and way-finding benefit is supported in literature reviewed [4, 15].

As discussed by Chan [15], the team also found that when objects were introduced in excess (doors without numbers in all maps, chairs in the large map, etc), these objects lost their uniqueness and were then less beneficial for way-finding and orientation.

> P10: "All the doors looked the same, so I had to find something that looked familiar before I knew where I was."
>
> P12: "In the small map the chairs were really helpful because they led straight to the target, but in [the large map] I basically ignored them because they were everywhere."

This highlights the focus of all subjects on identifying characteristics with which to anchor their memories and activate imagistic memory recall for navigation.

Of final note, however, is that participants who were in the Set 2 "control" group (not given anchor points) did eventually get comparable bearings of location.

> P10: I saw a long hallway and said to myself I did not go down a long hallway so I knew I had to turn as soon as I could."

In other words, by the last of the 4 trials, most participants in this group were able to get a general bearing on their location and described using a similar anchoring type of analysis to do so. It turns out that they used characteristic images of the hallways (ex. long hallways, hallways with no doors on either side, etc) as the new anchors. This may imply that given enough time, humans can differentiate small differences in even common images and use those differences in memory activation.

3.2.2 Emotional Recall

Additionally, emotions appeared to play a significant role in memory activation and conflict resolution. For example, use of some emotions appeared to help participants deciding which course was the best if the participant was uncertain:

> P3: I remembered, I think this is where I felt lost before. I remembered I felt lost and confused because the order of the numbers didnt make sense then, so I looked for the numbers that didnt make sense and took that direction
>
> P3: I recognized the intersection of 118 and 131 [though no numbers were actually on the doors] well, I didnt actually know it was that intersection, but it felt like it was.
>
> P4: "My gut said this was the wrong hallway, so I turned back"
>
> P5: "I got confused because the numbers seemed to jump unexpectedly".
>
> P8: "I'm pretty sure where I need to go once I find the table."

Unlike when participants were sure of their path, they often brought up how they "felt" when they were recalling uncertainty in their path. They often discussed their "gut feeling" if they didn't know why they decided to take a particular path or thought they had made a mistake. This seems to support the idea that emotions play a significant role in memory activation and conflict resolution [16]. Specifically, participants appeared to associate emotions with specific visual cues, and to help highlight or store a specific memory. If this is the case, it could help in learning by "earmarking" an unknown decision to see how it plays out.

In turn, even if participants can't explain why they take a particular path, its possible that their subconscious memory includes an emotional trigger which pushes them in one direction or the other. It's possible that these emotional responses help bring those subconscious memories to the surface.

The third interview set was more informative on the specific role of confusion in navigation (as discussed earlier). As with the prior examples, these emotions still played into participant confidence, and momentary confusion did help some participants activate action related memories in future trials. However, long term spatial confusion appeared to have detrimental effect on participants, causing them to ignore relevant object locations and path markers.

> P12: "I remember seeing the plants before, but I have no idea where they are relative to the room.....I remembered seeing them, then getting lost, then finding the room"
>
> P17: "Where am I?...What is happening?...I'm just turning hoping I'll find something...[after finding the target room] I have absolutely no idea how I got here. I just remember making a bunch of turns. Theres no way I'll be able to get back next time"

These quotes were provided in the context of the subject taking many turns with relatively unidentifiable objects, and (as verbally described) being disoriented and confused. While they passed many objects on the way to the goal, if they were in a state of confusion they stopped paying attention to those objects (ex. tables, chairs, hallway intersections, etc), and therefore had trouble recreating it in the subsequent trial. This asserts that a state of long term confusion may make people either forget established memory links or not commit links to memory in the first place (perhaps because the subject is not yet sure if those links will be useful).

3.3 Trajectory Analysis

As part of the interview process, subject's trajectories (path traversed through the map looking for target room) were recorded for later analysis. Two representative trajectories are shown in the figures below.

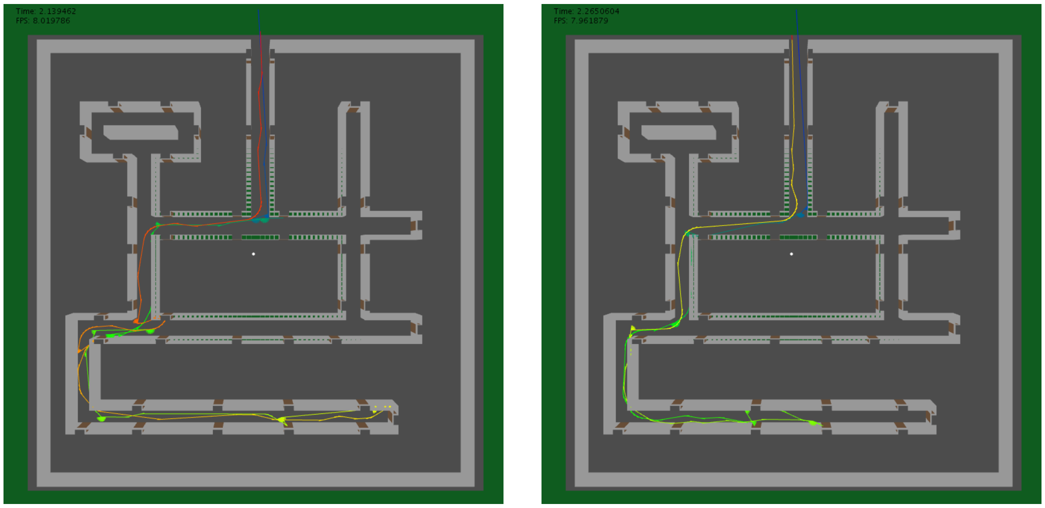


Figure 5: P4 Trajectories: (left) Room numbers available, (right) no room numbers available. Note the smoother trajectories as strategy moves from rules to imagistic activation

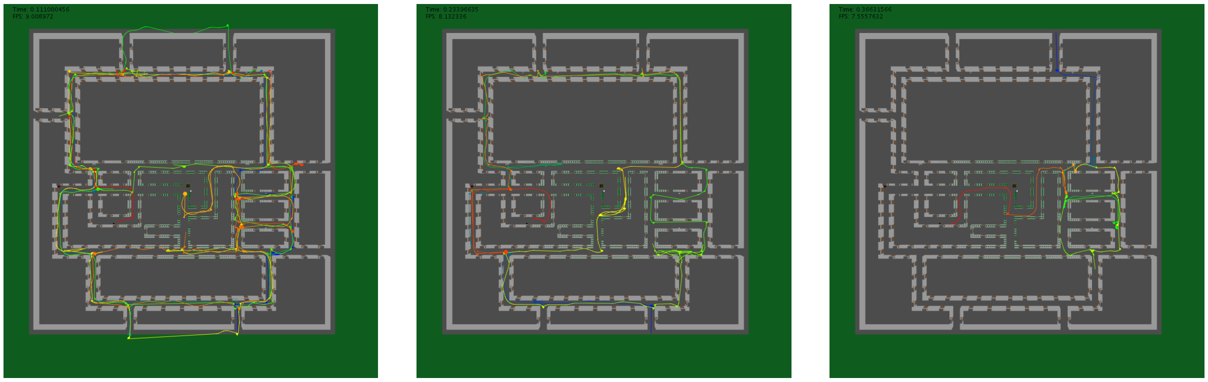
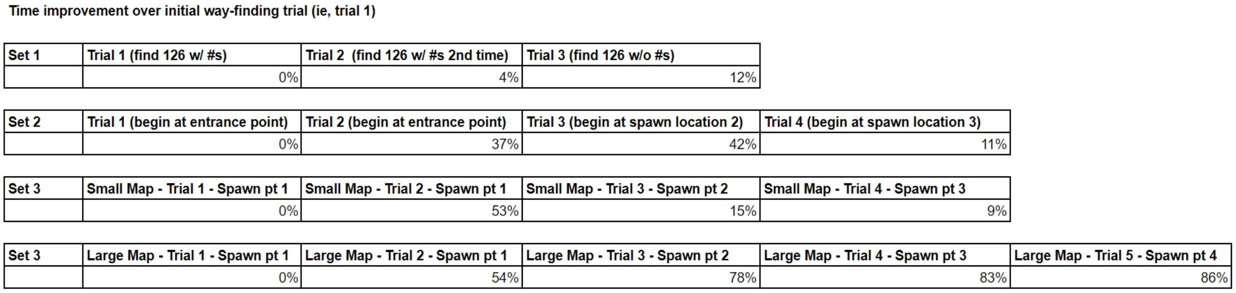


Figure 6: P12 Trajectories: No room numbers available, various objects available throughout. (left) 1st time through map (spawn point 1), (center) 2nd time through map (spawn point 1), (right) 3rd time through map (spawn point 2). Note that in each subsequent trial, the subject was able to reach the target in progressively less time and fewer repeated paths

From this analysis, it is evident that as subjects get more familiar with their environments and (as described previously) move from a rules strategy to an imagistic strategy, the paths get smoother and the participants progressively reach their target faster. This appears to involve greater confidence in their routes as well as less computational time at decision points since they visualize the necessary actions upon visual approach (as opposed to analyzing information in a rule framework at each point). While evident from visual analysis, the trajectory improvement can be seen quantitatively as well in the following figure:



Time improvement over initial way-finding trial (ie, trial 1)

Set 1	Trial 1 (find 126 w/ #s)	Trial 2 (find 126 w/ #s 2nd time)	Trial 3 (find 126 w/o #s)
	0%	4%	12%

Set 2	Trial 1 (begin at entrance point)	Trial 2 (begin at entrance point)	Trial 3 (begin at spawn location 2)	Trial 4 (begin at spawn location 3)
	0%	37%	42%	11%

Set 3	Small Map - Trial 1 - Spawn pt 1	Small Map - Trial 2 - Spawn pt 1	Small Map - Trial 3 - Spawn pt 2	Small Map - Trial 4 - Spawn pt 3
	0%	53%	15%	9%

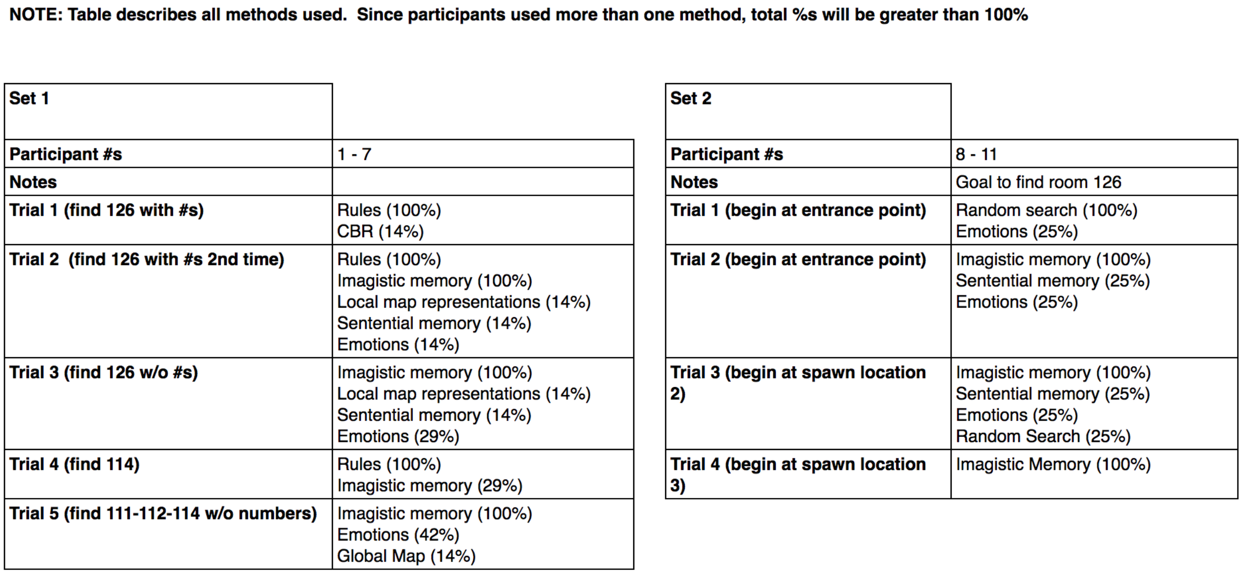
Set 3	Large Map - Trial 1 - Spawn pt 1	Large Map - Trial 2 - Spawn pt 1	Large Map - Trial 3 - Spawn pt 2	Large Map - Trial 4 - Spawn pt 3	Large Map - Trial 5 - Spawn pt 4
	0%	54%	78%	83%	86%

Figure 7: Average time improvement over initial way-finding trial (ie, trial one in each set)

Again, this data shows that in each subsequent trial, subjects are able to improve on their initial way-finding exploration to create a more direct path toward the goal. It is noted that the exact percentages should not heed much attention, since they are relative to how much time the 1st trial took on average (with set 3 large map taking the longest at an average 6 mins). Rather, the direction of improvement speaks to the ability of subjects to learn and the effects of changing spawn location for various map sizes.

3.4 Summary & Recap of Data Analysis

The previous subsections walked the reader through the collected data and accompanying logical deductions. This section will summarize the pertinent findings in the context of human cognition. The data can be quantified as shown in the table below, and the results can be grouped and discussed as follows:



NOTE: Table describes all methods used. Since participants used more than one method, total %s will be greater than 100%

Set 1	
Participant #s	1 - 7
Notes	
Trial 1 (find 126 with #s)	Rules (100%) CBR (14%)
Trial 2 (find 126 with #s 2nd time)	Rules (100%) Imagistic memory (100%) Local map representations (14%) Sentential memory (14%) Emotions (14%)
Trial 3 (find 126 w/o #s)	Imagistic memory (100%) Local map representations (14%) Sentential memory (14%) Emotions (29%)
Trial 4 (find 114)	Rules (100%) Imagistic memory (29%)
Trial 5 (find 111-112-114 w/o numbers)	Imagistic memory (100%) Emotions (42%) Global Map (14%)

Set 2	
Participant #s	8 - 11
Notes	Goal to find room 126
Trial 1 (begin at entrance point)	Random search (100%) Emotions (25%)
Trial 2 (begin at entrance point)	Imagistic memory (100%) Sentential memory (25%) Emotions (25%)
Trial 3 (begin at spawn location 2)	Imagistic memory (100%) Sentential memory (25%) Emotions (25%) Random Search (25%)
Trial 4 (begin at spawn location 3)	Imagistic Memory (100%)

Figure 8: Summary of cognitive tools used by interviewees

- Rules
  Rules are primarily used when the subject is in an unknown environment. The specific rules used vary depending on the situation. When numbers are available, the subject uses a number minimization approach, possibly a go-to since humans are exposed to similar CBR situations in hotels, apartments, etc. If not available, subjects tend to use a random search method (specific method varies), while noting unique objects along the path (if any) for later reference.

- Imagistic Reasoning
  As subjects get more familiar with their surroundings and the path, they begin to visualize their previous actions at identifiable intersections. When unique objects are available, these objects become anchor points with which the subject can orient themselves relative to their previous memories. Having these objects helped the subjects get to the target faster as long as they were identified in a previous trial near the time that the subject found the target. While the specific object used did not appear to play a significant role, the object had to be unique as more common objects lost their anchoring benefit for subjects. It is noted that when objects were not available, most participants were able (after some time) to create anchor memories out of hallway characteristics (length, number of doors, etc).

- Emotional Recall
  Emotions appeared to affect subjects way-finding by making it more or less likely that they would remember their path. The most common emotions were confusion and frustration. If subjects had momentary confusion, this could help them by activating associated action

memories when the subject found themselves in a similar momentary confusion state. however, if subjects were frustrated or the confusion lasted through multiple hallways, the effect was less beneficial, making subjects not pay attention to necessary anchor points for later orientation.

Employing these cognitive tools, subjects were able to learn their surroundings and improve in confidence and familiarity with the space, increasing their relative time to target for subsequent trials.

4 Discussion & Implications for Computer Model

4.1 Human cognition for Spatial Navigation

Initially, the team hypothesized that an agent in an unknown environment would use sentential rules or a random search process to find the target location. This idea was supported by the previous class research and by literature [11]. As a whole, this hypothesis is supported by the data collected.

The team assumed that this initial process would allow participants to navigate the area in future trials by developing an allocentric map model, knowing where they are in the map relative to the target location. As seen from the data and supported by literature, it became apparent that humans tend to use visual cues for navigation as opposed to global cognitive maps [15, 17, 18]. Indeed, it appears that humans tend to focus on egocentric imagistic reasoning to identify anchor points, as well as emotions to help guide decision making (i.e., confidence in route).

4.2 Representation and Data Structures

The problem that this project addresses is one of way finding, learning, and path planning in a 2-D urban indoor setting. The experiments were conducted to extract information on the cognitive processes involved in this exercise, and the human agents operate in a simulation environment that is constrained to static one level floor plan. Shown in Figure 9 is a path taken by one of the test subjects. A feature that is common amongst most trajectories is that decisions are made at hallway junctions.

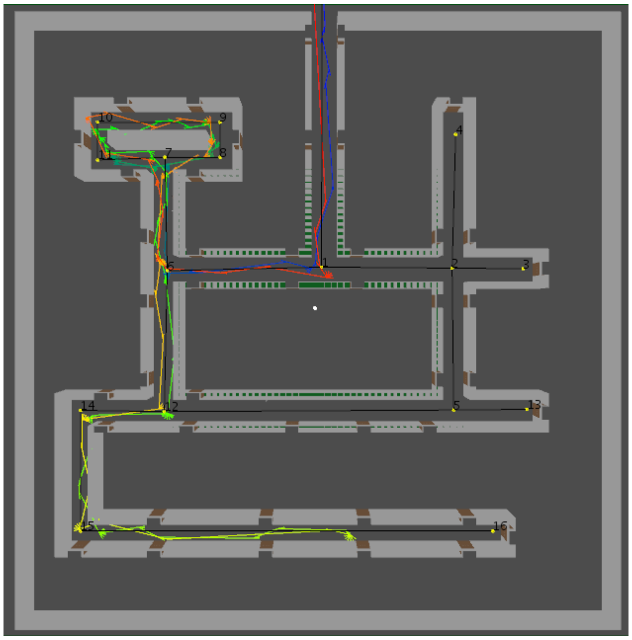


Figure 9: Example trajectory indicating decision points

This means that once the subject makes a decision take an action (choose heading) at a junction, they commit to that action until they have arrived at the next junction, turn or dead end. This observation allows for the map and the decision making problem to be abstracted and represented using a graph network. Figure 10 shows an example of the graph structure of the current floor plan. By placing a node at each decision point and representing the hallways that connect them using edges, the problem is significantly simplified.

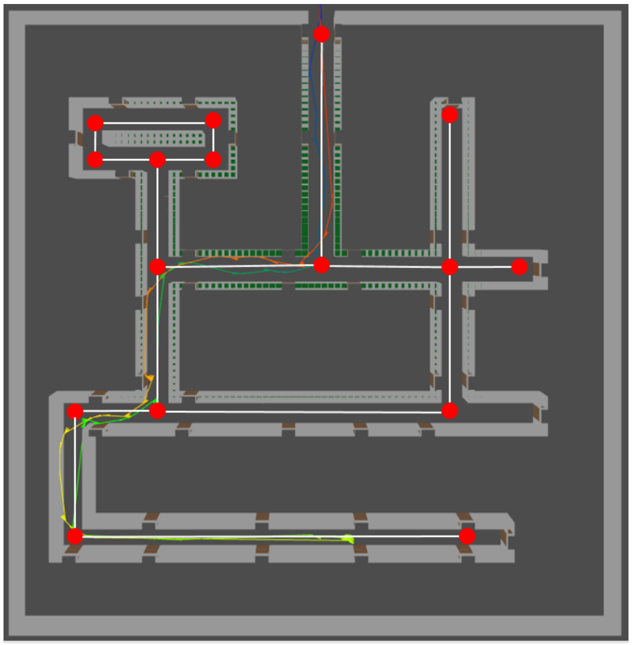


Figure 10: Graph overlaid on floor plan

Although the graph world is simpler to reason over, the challenge brought on by this abstraction is one of communication between representations. In order to overcome this, the architecture is designed such that only the visibility and agent control modules have to interact (wrap) with the simulation environment. The visibility module converts observations (allocentric vectors to visible objects) into ordered lists associated with a node or an edge. Once this information is transformed into graph world, other modules are able to consume and produce decision. The decisions produced are then relayed to the action module that leverages a lower level controller to move the agent in the 2-D simulation environment.

4.3 Algorithms

The algorithms implemented in the agent are explained in this section. The architecture is divided up into Visibility, Long-term Memory, Planning, Learning and Agent Control modules. The system overview is shown in Figure 11 and the modules are discussed in more detail.

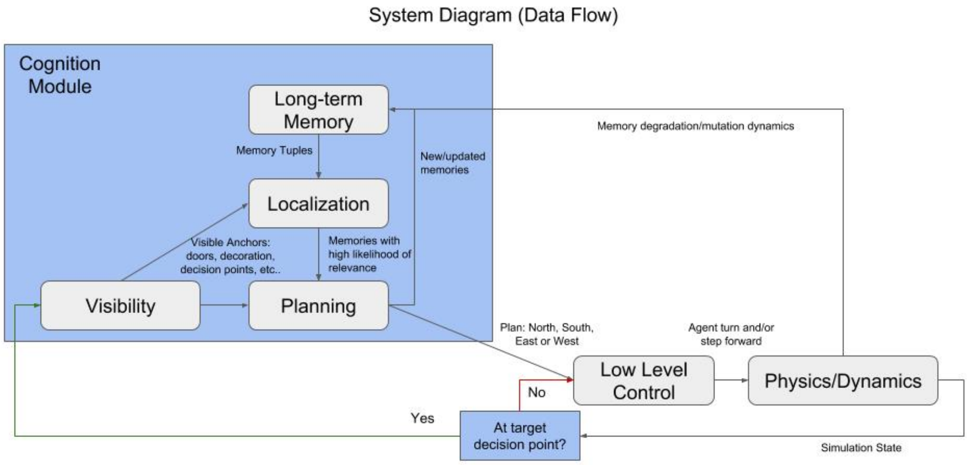


Figure 11: Overview of the system algorithms

4.3.1 Visibility and Perception

The agent must be able to perceive its surroundings and transform the symbols into consumable representations. These representations will be called observations.

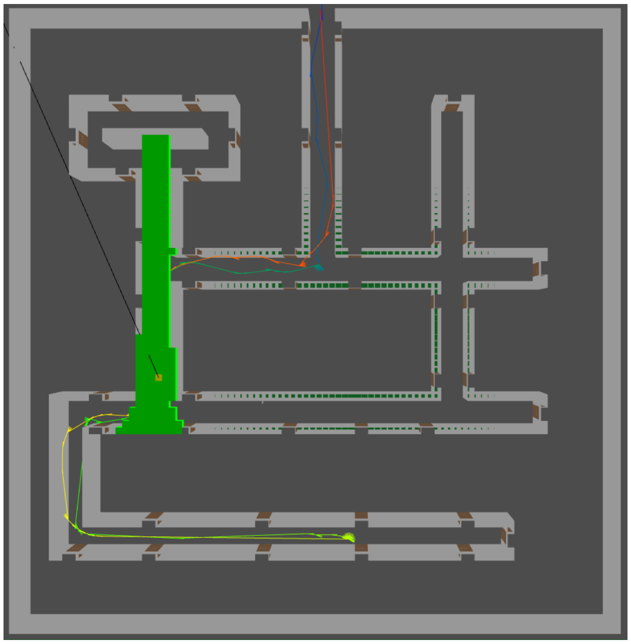


Figure 12: Visibility map in the grid world

An example of the perception module taking observations is shown in Figure 12. The 2-D continuous world is discretized so that a visibility map can be generated at the given location. The visibility map is used to identify visible objects in the 2-D environment and extract relevant spatial information. Observations are stored as vectors from the agent's egocentric perspective to each object in the visible space. The class Relation has the following structure.

```
class Relation:
vector v; //relative position vector (2D) from self to object
int type; //used to differentiate between Doors, Decorations, Decision Points, etc...
//types:
//0 = door
//1 = decision point (4-way)
//2 = decision point (3-way)
//3 = decision point ('corner' (2-way))
//4 = decision point ('dead end' (1-way))
//5+ = cell.decorationID + 5
```

4.3.2 Long-term Memory

The Long-term memory module accumulates and stores Observations (in the Relation structure) and associates a confidence score (c) against each one. The confidence score associated with a memory is used to inform the agent how likely it is reach the goal state by remembering and following the action taken when that memory was recorded. As will be discussed in the Learning subsection, the confidence score is analogous to the *value* of a state in Markov decision processes (MDPs). The

Memory class has the following structure.

```
class Memory:
ArrayList Relation observation; //anchor—vector pairs associated with this memory
float confidence;
int action;
```

An instance with the structure shown above is appended to the Long-term Memory module every time the agent visits a node.

4.3.3 Localization

The agent is imbued with the ability to localize itself using its current observations and the memories it has accumulated over past experiences in the map. The familiarity score (f) is used to measure similarity between the current observations and those stored in long-term memory. This is computed by measuring the normalized differences between observation and memory vectors of same anchor type (visible object type) across all memories in the long-term memory module. In order to account for all possible translation and rotations, the computation entails iterating over all possible vantage points and orientations for a given observation and memory and picking the maximum value to produce a sensible familiarity score. The familiarity score ranges between 0 and 1 with 0 indicating no familiarity and 1 indicating perfect recognition.

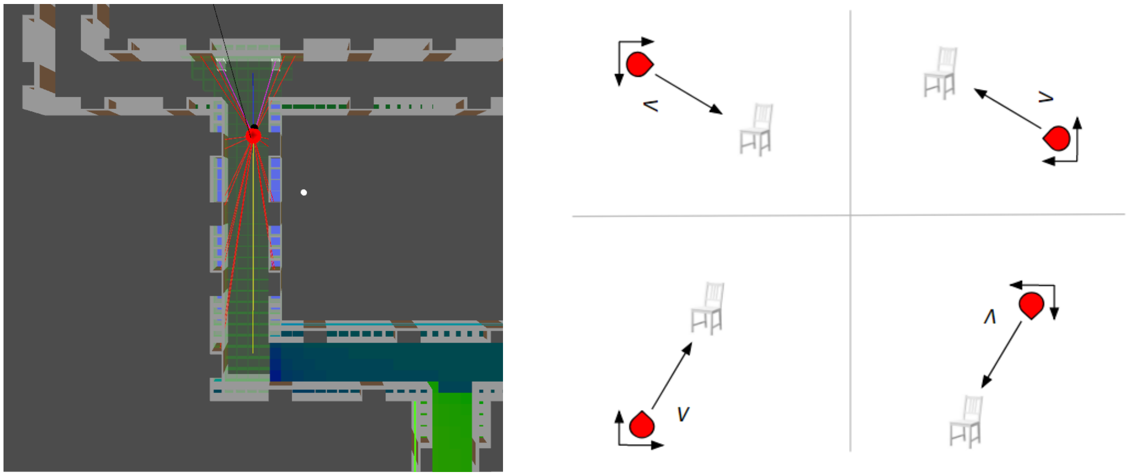


Figure 13: Left: The image shows the agent collecting observation in the form of objects and respective position vectors as it traverses the environment indicating the importance of the order in which objects are recorded. Right: The localization algorithm accounts for all possible orientations by computing familiarity over all four rotations and picking the maximum.

4.3.4 Learning

In the first episode, the agent focuses on frontier exploration and hence prioritizes exploring nodes that it least believes it has seen before (chooses node with lowest f score in visible space). When it eventually reaches the goal state, the last few memories are reinforced by updating their confidence values to be higher than previous values. In subsequent episodes, each time the agent explores a node that localizes with a memory having a high confidence, the previous memory is updated to have a higher confidence as well. Over many episodes, this process backpropagates the value associated with each memory thus encouraging the agent to take the "right" actions when observations trigger high confidence memories. This reinforcement mechanism is leveraged in parallel with the addition of memories to long-term memory which is an essential mode of learning itself.

c = Confidence
λ_1 = Learning rate or strength of near-goal memories
λ_2 = Learning Rate or strength of near-confident state memories

Algorithm 1 Reinforcement Algorithm

```
if current state is goal state then
    for last 3 memories $m_i$ do
        $c_i \Leftarrow c_i + \lambda_1^i$
else if current state is not goal state then
    if current memory has $c_i > 0$ then
        $c_{i-1} \Leftarrow c_{i-1} + \lambda_2$
    else if current memory has $c_i = 0$ then
        $c_{i-1} \Leftarrow c_{i-1}$
```

The parameters λ_1 and λ_2 represent the increment in confidence of a given observation-action pair when the observation was made near the goal state (less than 4 steps away) and when the observation was made near a confident state (less than 2 steps away) respectively. The parameters has been tuned empirically to achieve a nominal learning rate when compared against human agent performance.

$\lambda_1 = 0.3$
$\lambda_2 = 0.05$

4.3.5 Inference and Planning in the Presence of Emotions

Planning entails using the localization module's outputs, confidence c and familiarity f, alongside the data passed on by the visibility module to determine what action the agent should take. If the agent has localized itself (familiarity $f > threshold$) to a memory with a non-zero associated confidence, then it takes the action it remembers taking when it recorded the memory. If that is not the case, but the agent sees a node in its visibility graph that seems to have a non-zero confidence, it makes the decision to move toward the node that it thinks has highest familiarity but only with a probability of the familiarity score of that node. This randomness injected here and in other steps of the algorithm incorporates the stochasticity observed in human trials and also allows the agent to gracefully deal with loops. If the agent has never been to the goal state (still exploring the map for the first time), it prioritizes taking actions it has not previously taken when the memory was recorded in the past. This encourages the agent to explore new and unfamiliar nodes as it attempts to find the goal state. If a novel action is unavailable, the agent takes a random action. Interview data and trajectory analyses have shown that human agents tend not to visit a node behind them unless they are forced to (encountering a dead end). All the action decisions in the algorithm reflect this behavior. The pseudo-code is shown below.

f_1 = Familiarity Threshold 1
f_2 = Familiarity Threshold 2
f = Familiarity
c = Confidence
a = Actions available
a_{novel} = Novel actions available
$bool_{nwe}$ = Does visible node exist North, West or East of current agent heading
$bool_{gr}$ = Was goal reached in a previous episode

Algorithm 2 Wayfinding Algorithm

```
if at current node $f > f_1$ and $c > 0$ and $a > 0$ then
    Move to node that maximizes $c$
else if a visible node exist with $c > 0$ and $f > f_2$ then
    Move to node with $c > 0$ and maximizes $f$ with probability $f_{max}$
else if a visible node exists with $f > f_1$ and $bool_{gr}$ is FALSE then
    if $a_{novel} > 0$ then
        Choose random action from $a_{novel}$
    else
        Take random action
else if at current node $f < f_1$ then
    if a visible node exists with $f > f_2$ and $c > 0$ then
        Move to node that maximizes $f$
    else if $bool_{gr}$ is TRUE and a $bool_{nwe}$ is TRUE with $f > f_1$ then
        Move to node that maximizes $f$ with probability $f_{max}$
    else if $bool_{gr}$ is FALSE and $bool_{nwe}$ is TRUE then
        Move to node that minimizes $f$
```

The emotions incorporated into the algorithm, Confidence, Confusion and Familiarity, allow the agent to make decisions about actions conditioned on long-term memory and also change strategies (ex: random actions when confused) when it thinks it is confused. Trajectory analyses and interviews showed that when human subjects were confused, they tended to walk in loops and take random actions. It was seen that this was a state that correlated with high familiarity and low confidence. This implied that there could be multiple locations in the map that "look" the same but do not lead to the goal state in the expected sequence of nodes. Hence, taking actions informed by localized memories inform does not have to lead to localized memories with increasing confidence. The learning algorithm then weights down the confidence associated with these memories. A high familiarity memory does not have to carry high confidence, thus inducing a state of confusion.

4.3.6 Agent Controller

The agent controller is the last module in the cognitive cycle and translates the planning module's intentions into actions. The planning module informs the controller what the next beacon is and the controller moves the agent (translation and rotation) in the continuous 2-D environment to approach the new beacon.

5 Validation, Insight, and Implications

Having built the cognitive agent as described above, the team sought information on how to validate the agents cognitive processes are similar to those of human agent. The answer to this validation question was approached by looking at the following behavioral characteristics:

5.1 Agent Cognitive Toolset

Does the agent implement similar tools in navigational decision making?

From the research conducted, humans cognitive toolset depends on if they are conducting initial area exploration or repeated way-finding. For initial exploration, the predominant strategy is to use rules to explore the area. Since room numbers were not available, the dominant strategy that human agents would use would be a random search, with a preference for going toward unexplored areas rather than previously explored areas (i.e, trying not to go back to the same place its been, if possible). As seen in Figure 14, the agent had a comparable amount of confusions and uncertainty (signified by repeating previously explored paths) as the chosen representable subject. An investigation into the programs output file also shows that it is trying to go to areas that are least familiar to it, thus attempting to explore unknown areas as much as possible.

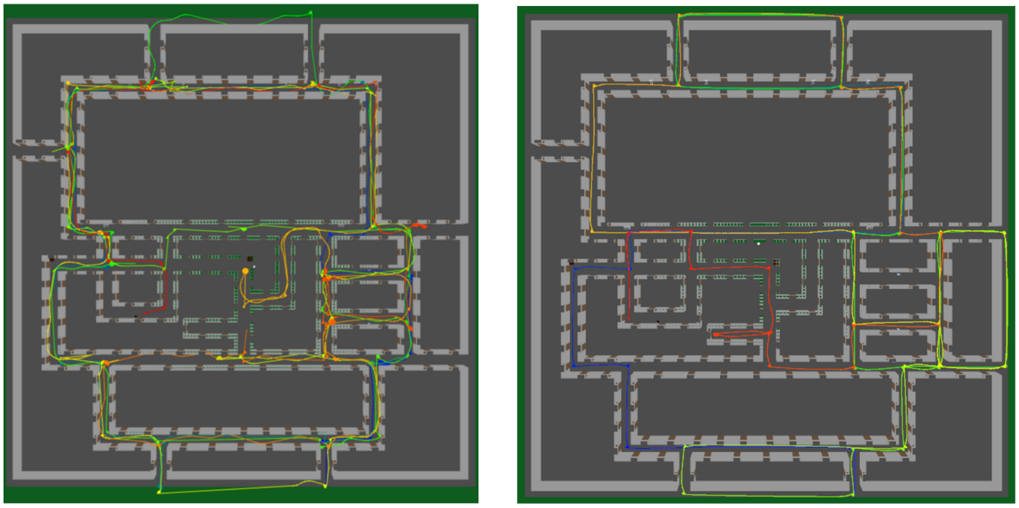


Figure 14: Comparison of Agent Trial 1 to P12 Trial 1

5.2 Agent Learning

How does the agent learn? How does it describe its learning?

From the interviews conducted, human agents learn an area by developing egocentric imagistic memories to create observation-action pairs. They use object or image landmarks to activate connected action memories that help them navigate the space in the future. Similarly, their emotions affect this memory development. Momentary flashbulb emotions appear to help with the connections (increasing familiarity and confidence) whereas long term confusion or frustration tend to hinder memory connections (decreasing confidence), making the human agent act randomly.

The agent works in a similar manner. By developing memories during its initial exploration, it is able to look at its surroundings, see if the surroundings match a memory it has (the familiarity index), and if so, it can make the connection between that memory and the action it took last time if that action led to the goal (increased confidence). Also, the agent can get confused if it can't figure out where it is. This confusion leads it to act randomly, trying to get to a place that has some familiarity to it.

Importantly, the agent is able to communicate both the learning and emotions to others via its log. As a human may explain why it took a turn (”that turn looks right”), the agent can act in a similar manner (”that node is familiar to me”).

5.3 Agent Performance Improvement

Is the agent able to utilize its learning to improve performance over time?

Of course, learning should have a goal. In the case of human agents, they were able to apply their cognitive processes to learn, and improve their performance over subsequent trials. Indeed, the agent too shows tremendous improvement over subsequent trials as seen in the results of Figure 15, the agent's ability to get to the target in a shorter amount of time improves as it becomes more familiar with the area and gets more confident with its path. Similarly, the visual improvement shown in Figure 15 indicate that the agent is getting to its target with progressively less overlap in existing areas and with fewer directional changes - very similar to the results shown in Figure 6. Interestingly, changing the spawn point did change the performance of the agent somewhat (specifically lesser time improvement) - results that are also seen in the human trials (Figure 7) and reinforce the comparability of the computational agent with human subjects.

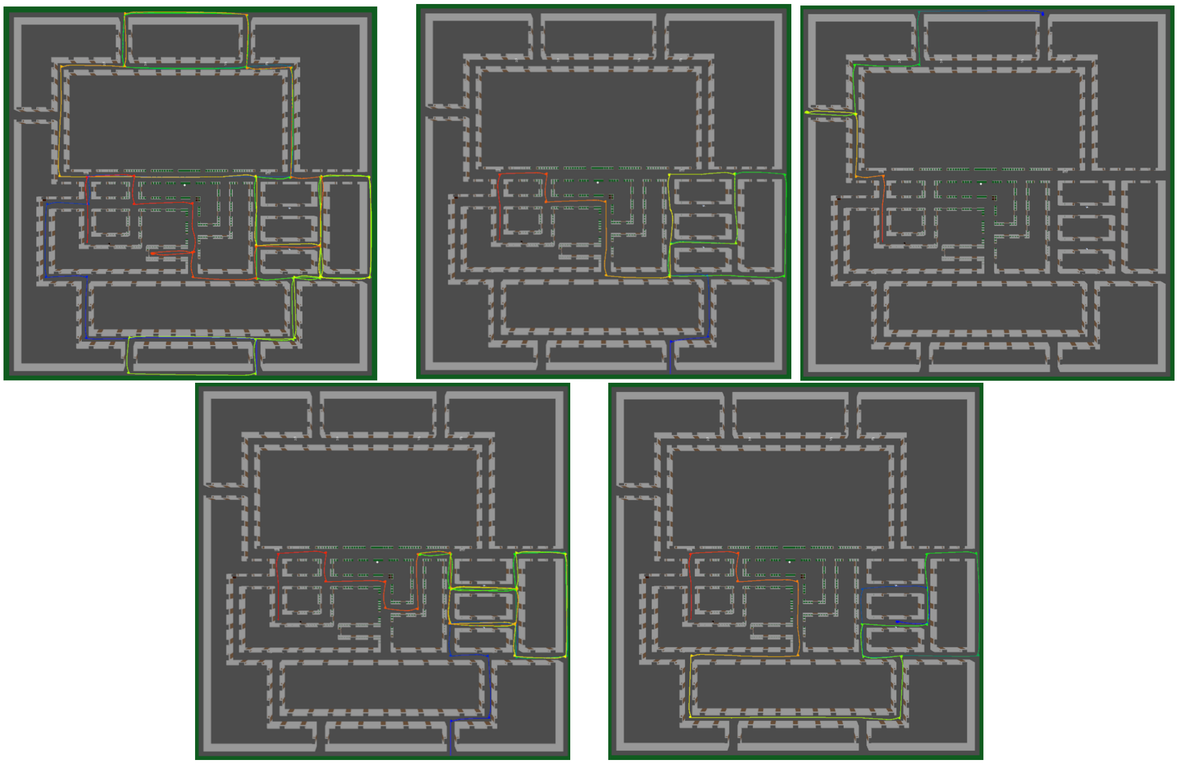


Figure 15: Agent trajectories for Trials 1-5

5.4 Insights and Implications

This study highlighted some interesting results and implications for understanding human cognition and design for navigation. On the human cognition side, two unexpected insights arose that are worth mentioning. First, while navigational landmarks were important in helping agents learn a space faster, given enough time, even the most complex or sparse environments can be learned and improved upon. Additionally, while agents do learn and improve on routes over time, sudden changes in expectations (as seen through different spawn points which may correspond to entering a building from a different entrance) may cause momentary confusion or decreased in observed learning benefits. Even so, these momentary changes still provide better way-finding results than initial exploration, and the agent can "recover" from momentary confusion faster as the area is learned better.

These results also show the impact of landmark objects on navigation. These have particularly interesting implications in building design both for humans and for robotic agents. Knowing that unique beacons are essential to navigational learning and faster initial exploration, buildings designs could focus on creating these landmarks to help pedestrians navigate the space. Further, as technology advances and self-navigating AI becomes more dominant (delivery, cleaning, etc), the benefits of building complexes that support both human and computational navigation equally will be quite important. This and future work could help inform the necessary components for those goals.

6 Future Work

While the team attempted to model human cognition in way-finding, the project time frame limited the ability to fully investigate all aspects of this process. Some areas of future work should look at the following:

- Differences in anchor objects
  The team found that different anchor objects memorized with different degree in our participants. For example, in a large map in set 3, participants tend to remember tables more than chairs. Our study was not designed to answer this question, which leaves the question to be solved in the future study.

- Gender effects
  While the team did not find any significant gender effects on way-finding in this project, literature [19, 20] suggested these effects should exist. Initially, our study was not designed in a way to look for the gender differences, but still, there is possibilities that the effects could be observed in different map orientations or interview processes.

- Analogies & Case based reasoning
  The team observed that human agents utilized their previous experiences to initially navigate the maps. Especially, we found participants who had experiences in first person viewpoint video game performed better than participants who do not have. However, to focus on the learning aspect of the agent, the team assumed limited prior knowledge from other scenarios when the agent was introduced to a new map (ex. if numbers are available, numbers tend to go in sequentially increasing or decreasing order). However, integration of prior knowledge could help the agent more effectively navigate a new map. This integration could be investigated

further by conducting a focused study (ex. additional interview set) on how humans utilize CBR.

- Observer dynamics
  How does observing someone else going through the area affect the observer's knowledge and way-finding abilities? The team did find that observers were able to learn the area to some degree, but did not study these observer effects in detail.

7 Conclusion

The team conducted interviews to identify how human subjects navigate through new and revisited spaces. Human agents tended to rely on available rule-sets when exploring new spaces, while reinforcing observation-action activation connections that helped lead toward the target. In the revisited spaces, humans used images to activate the memories of previous trials with associated action. Here, we could observe that emotions were implemented by either assisting in memory creation or impeding memory creation based on the nature and length of the emotion. In the end, humans were able to use these memories to learn and improve performance over repeat trials

The team was able to utilize the research conducted on human agents to develop a computational cognitive agent with similar features. The agent was able to explore new spaces while creating memories and utilizing emotional states via its confidence and familiarity metrics. Additionally, the agent was able to communicate its learning methodology to others, even noting when its emotional state and how that affects it decisions.

This project provided unique insight into the human indoor-navigation process and how we can design computer agent to think and act as humans do. Indeed, this work has tremendous benefits to existing technologies, such as improving an autonomous navigation system or even in designing floor plan in an office building. The results we got here would be a stepping stone on creating agents who can navigate unknown areas, learn in the process, and more importantly, improve over time.

References

[1] H. Zhang and C. Ye, "An indoor wayfinding system based on geometric features aided graph slam for the visually impaired," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 9, pp. 1592–1604, 2017.

[2] J. C. Torrado, G. Montoro, and J. Gomez, "Easing the integration: A feasible indoor wayfinding system for cognitive impaired people," *Pervasive and Mobile Computing*, vol. 31, pp. 137–146, 2016.

[3] E. C. Tolman, "Cognitive maps in rats and men." *Psychological review*, vol. 55, no. 4, p. 189, 1948.

[4] N. Burgess, E. A. Maguire, and J. O'Keefe, "The human hippocampus and spatial and episodic memory," *Neuron*, vol. 35, no. 4, pp. 625–641, 2002.

[5] R. F. Wang and E. S. Spelke, "Human spatial representation: Insights from animals," *Trends in cognitive sciences*, vol. 6, no. 9, pp. 376–382, 2002.

[6] T. I. Brown, V. A. Carr, K. F. LaRocque, S. E. Favila, A. M. Gordon, B. Bowles, J. N. Bailenson, and A. D. Wagner, "Prospective representation of navigational goals in the human hippocampus," *Science*, vol. 352, no. 6291, pp. 1323–1326, 2016.

[7] F. Chersi and N. Burgess, "The cognitive architecture of spatial navigation: hippocampal and striatal contributions," *Neuron*, vol. 88, no. 1, pp. 64–77, 2015.

[8] N. Burgess, "Spatial memory: how egocentric and allocentric combine," *Trends in cognitive sciences*, vol. 10, no. 12, pp. 551–557, 2006.

[9] A. D. Ekstrom and E. A. Isham, "Human spatial navigation: representations across dimensions and scales," *Current opinion in behavioral sciences*, vol. 17, pp. 84–89, 2017.

[10] T. Hartley, E. A. Maguire, H. J. Spiers, and N. Burgess, "The well-worn route and the path less traveled: distinct neural bases of route following and wayfinding in humans," *Neuron*, vol. 37, no. 5, pp. 877–888, 2003.

[11] N. Vukovic and Y. Shtyrov, "Cortical networks for reference-frame processing are shared by language and spatial navigation systems," *NeuroImage*, vol. 161, pp. 120–133, 2017.

[12] J. R. Anderson, *Rules of the mind.* Psychology Press, 2014.

[13] M. Zhao and W. H. Warren, "How you get there from here: Interaction of visual landmarks and path integration in human navigation," *Psychological science*, vol. 26, no. 6, pp. 915–924, 2015.

[14] A. D. Ekstrom and C. Ranganath, "Space, time, and episodic memory: the hippocampus is all over the cognitive map," *Hippocampus*, 2017.

[15] E. Chan, O. Baumann, M. A. Bellgrove, and J. B. Mattingley, "From objects to landmarks: the function of visual location information in spatial navigation," *Frontiers in psychology*, vol. 3, p. 304, 2012.

[16] M. Palmiero and L. Piccardi, "The role of emotional landmarks on topographical memory," *Frontiers in psychology*, vol. 8, p. 763, 2017.

[17] E. A. Maguire, N. Burgess, and J. OKeefe, "Human spatial navigation: cognitive maps, sexual dimorphism, and neural substrates," *Current opinion in neurobiology*, vol. 9, no. 2, pp. 171–177, 1999.

[18] J. R. Manning, T. F. Lew, N. Li, R. Sekuler, and M. J. Kahana, "Magellan: A cognitive map–based model of human wayfinding." *Journal of Experimental Psychology: General*, vol. 143, no. 3, p. 1314, 2014.

[19] C. A. Lawton, "Gender differences in way-finding strategies: Relationship to spatial ability and spatial anxiety," *Sex roles*, vol. 30, no. 11-12, pp. 765–779, 1994.

[20] A. Bosco, A. M. Longoni, and T. Vecchi, "Gender effects in spatial orientation: Cognitive profiles and mental strategies," *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, vol. 18, no. 5, pp. 519–532, 2004.