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cogARCH: Simulating Wayfinding by Architecture in Multilevel Buildings

ABSTRACT

Findings from cognitive science link the architectural complexity of multilevel buildings with occupants' difficulty in orienting and finding their way. Nevertheless, current approaches to modelling occupants' wayfinding reduce the representation of 3D multilevel buildings to isolated 2D graphs of each floor. These graphs do not take account of the interplay between agents' 3D field of view and buildings' 3D geometry, topology, or semantics, yet these are necessary to inform occupants' path differentiation during wayfinding. Instead, agents are often modeled as unbounded and rational, able to calculate complete paths towards goals that are not immediately visible using direct routing algorithms. In turn, simulated behavior in most cases is unrealistically optimal (e.g. shortest or fastest route). This gap may hinder architects' ability to foresee how their design decisions may result in suboptimal wayfinding behavior, whether intended or not. To bridge this gap, the paper presents cogARCH, a computational, agent-based simulation framework. cogARCH is grounded in research on spatial cognition and heuristic decision making to support pre-occupancy evaluation of wayfinding in multilevel buildings. To demonstrate the relevance of cogARCH to architectural design, we apply it to assess wayfinding performance across three architectural variations of a multilevel education building. Preliminary results showcase significant variability in cognitive agents' wayfinding performance between building scenarios. In contrast, behavior of shortest-path agents sampled across respective conditions displayed significantly less variance and thus failed to reflect potential effects of architectural changes on wayfinding behavior.

Author Keywords

Pre-occupancy simulation; Cognitive agents; Wayfinding; BIM; Agent-based simulations;

ACM Classification Keywords

I.6.1 SIMULATION AND MODELING: I.6.5Model Development; J.6 COMPUTER-AIDED ENGINEERING; I.2 ARTIFICIAL INTELLIGENCE

1 INTRODUCTION

Within the building simulation community, research in the area of pre-occupancy simulations has mainly focused on modelling egress evacuation[2], crowd behavior[22], and most recently building narratives[24, 18]. These studies focus on modeling collaborative behaviors to analyze macroscale patterns. As a result, less emphasis is placed on modeling low-level, microscale behaviors such as wayfinding. Instead, direct routing algorithms (e.g. A*) are used to simulate obstacle and crowd avoidance along a shortest path between origin and destination pairs. This approach overlooks agents' bounded 3D field of view and cognitive limitations observed during wayfinding in unfamiliar environments, and especially in multilevel buildings[10, 12].

Cognitive science research on wayfinding in multilevel buildings has linked architectural complexity with occupants' difficulty in orienting and finding their way[20, 10, 12]. In particular, discontinuous and discretized horizontal and vertical sightlines from decision points to such key building elements as vertical circulation, entrances, and exits is associated with occupants' having to rely on fragments of perceived or stored information to support wayfinding towards goals that are not directly visible[10, 12]. The incompleteness of this information may result in erroneous decisions, loss of orientation, confusion, and frustration[17, 10, 12].

Nevertheless, current approaches to simulating movement in buildings decompose the spatial complexity of 3D multilevel buildings into isolated 2D graph representations of each floor[15]. The main shortcoming of this approach is its inability to support 3D field-of-view calculations in a way that captures agents' visual perception of multilevel spaces. Representing both the navigation space and agents' vision in 2D does not allow dynamic simulation of occupants' field of view through a vertical void in the building, such as an atrium or staircase and towards potential goals at different floors. Whereas this limitation plays a minor role in wayfinding simulations set in single-level environments, it poses a barrier to wayfinding simulations set in multilevel buildings.

Moreover, architectural, semantic, and topological features linked with 3D building configurations are often not encoded in the navigation space, although these have been reported to influence occupants' ability to differentiate between path choices[5, 3]. Instead, agents are modeled as essentially unbounded and rational and given complete knowledge of the navigation environment[15]. In turn, simulated behavior in most cases is optimal (i.e. shortest or fastest route) and fails to account for reported findings regarding loss of orientation as a function of vertical travel[20], specific wayfinding strategies observed in multilevel buildings[10], and expectations, that might be unmet, concerning the association of external cues with typical building destinations[5]. In the absence of an integrated simulation model that reflects both the cognitive and the architectural complexity of wayfinding in multilevel buildings, architects are not necessarily able to foresee the ways in which their design decisions may result in suboptimal wayfinding behavior, whether intended or not.

This paper aims to bridge this gap and make a direct contribution to the building simulation community and in particular to occupant-centered simulations. We thus present the development of cogARCH: a computational, agent-based simulation framework to simulate wayfinding in multilevel buildings. cogARCH draws on research from spatial cognition and heuristic decision making to support pre-occupancy evaluation of wayfinding during the design process. The paper's main contributions are threefold: (1) a parametric cognitive agent model grounded in theories of spatial decision making and spatial analysis, and incorporating reported wayfinding strategies in multilevel buildings; (2) a combined approach to simulating agents' visual perception in multilevel building space that integrates 2D isovist fields and a 3D field of view; and (3) an automated preprocessing pipeline to generate a 3D, hierarchical and semantically rich navigation space from a 3D Building Information Model (BIM).

To demonstrate the relevance of cogARCH to architectural design, we perform a sensitivity analysis and simulate wayfinding across three architectural variations of a multilevel education building. To highlight the need to model the interplay between 3D field-of-view and complex geometry of multilevel space, we consider architectural variations related to vertical visibility, including variation in building materials (e.g. glass vs. concrete) and floor permeability (e.g. addition of atria voids). Preliminary results showcase significant variability in cognitive agents' wayfinding performance between building scenarios. In contrast, the behavior of shortest-path agents sampled across respective settings displayed significantly lower variance. Finally, we briefly discuss planned calibration and validation experiments in virtual reality and critically assess the relevance of the proposed method to inform architectural design decisions.

2 RELEVANT STUDIES

2.1 The Process of Wayfinding in Buildings

Visual information is considered a primary input to wayfinding decisions[3, 10]. The building design may facilitate or hinder visual access in both the horizontal and vertical axes with walls, doors, choice of materials, atria, and shafts. Information perceived by occupants is used to construct internal representations both of the local choice set and of global search structures, depending on the building's configuration[23].

Various attempts have been made to quantify visibility based on 2D floorplans using space syntax methods[3, 1]. Both global and local measures of visibility can be described using these methods. For instance, axial map analysis focuses on global measures of visibility[8]. In contrast, isovists[1, 3]describe the local spatial properties of a visible area from a given observation point using viewshed polygons. Amongst 18 isovist measures[1, 3], building locations at which the area of each isovist polygon is larger have been correlated with the locations of decision points[3].

A further link between visible information and background expectations in directed wayfinding in unfamiliar buildings is made by Frankenstein et al[5]. They conclude that occupants' background expectations regarding the association between perceived environmental cues and locations of typical building destinations predict local wayfinding choices[5]. Environmental cues are broadly defined and include configuration, materials, objects, people, and activities. Results demonstrate that building destinations such as auditorium, main exits and restrooms were associated with more central and public locations. In contrast, destinations such as rear exit, entrance to the cellar, and broom closet were associated with peripheral locations. Central locations were also rated as more public than peripheral ones. Specific environmental cues were significantly associated with some goal destinations; for instance, a chair was rated as indicative of a waiting area.

The ability to differentiate between local choices is crucial and depends on both the level of architectural differentiation between path choices[23] and occupants' reasoning on the basis of background expectation, local heuristics, and search strategies. Hölscher et al[10] provide an overview of the types of strategies that occupants employ in multilevel buildings. Novice occupants are most likely to follow a central-point strategy of finding one's way by sticking as much as possible to central and public parts of the building, even if this requires considerable detours. More complex strategies include the direction strategy: choosing routes towards the horizontal position of the goal as directly as possible[3], irrespective of level changes. In contrast, the floor strategy is applied when occupants aim to reach the floor of the destination first, irrespective of the horizontal position of the goal. Occupants familiar with the building tend to rely on either of the complex strategies. cogARCH uses these findings to provide a formal model in which expectations, strategies, and heuristics are used to simulate unaided and directed wayfinding in multilevel buildings.

2.2 Wayfinding Simulation Approaches

Various models of human navigation exist, most of which are grounded in the field of pedestrian dynamics. In this field, the use of microscopic models is becoming especially prevalent to decompose the complexity of collective emergent behavior by modeling a single individual agent. The majority of microscopic models applied to simulate navigation include three interconnected layers; a strategic layer in which agents choose between possible destinations to form an activity schedule[4], a tactical layer that focuses on route choice and path planning[9], and an operational layer that describes occupants' local 'steering behavior,' such as obstacle avoidance, speed, and acceleration[7].

The tactical layer models path planning towards a destination, essentially modeling the process of wayfinding. However, the destination is usually given to agents explicitly without them having to search for it on the basis of perceived information. In such cases, the simulation model is focused on path-planning, assumes global knowledge, and uses graph-based routing methods to calculate a walking path from an origin to a destination in accordance with some optimization criteria (e.g. distance, speed, density, etc.).

Approaches to generating navigation graphs from either 2D or 3D building geometries are various[9] and could be broadly classified into (1) semantic approaches that identify objects and relations between them; (2) topological methods that exploit visual connectivity and accessibility between semantic or geometric structures in space, such as rooms; (3) metric approaches such as occupancy grids that describe the distance and angle between locations in space; and (4) hierarchical models[13] that propose a multilevel hierarchical representation combining two or more of these approaches to model indoor navigation space.

Once a navigation graph is generated, a distinction is made between egocentric and allocentric routing algorithms. Direct routing solves the routing problem by providing an optimal path to the destination based on shortest or fastest path solutions. In contrast, iterative routing algorithms provide the next node to visit stepwise based on local optima. These algorithms are often used in egress simulations where agents are used to simulate evacuation to one or more exits. Given that agents have full knowledge of the navigation environment, the process of uninformed search using perceived environmental information is eliminated. Instead, agents calculate a shortest path towards a goal destination, regardless of its visibility. The main considerations that govern agents' movement are distance minimization, obstacle avoidance, and crowd evasion.

Cognitive approaches to simulating navigation and wayfinding have mostly focused on wayfinding aided by externalized symbolic information, such as signage, or on undirected wayfinding (i.e. exploration). Penn and Turner[16] developed an agent that perceives a space and infers spatial relations from a lookup table that encodes global measures of a visibility graph. This agent has access to cells captured in its 2D field of view and moves towards the cells with the highest visual connectivity value. Although this approach takes account of agents' bounded visibility, information provided relates to global measures describing the buildings' configuration beyond agents' natural perception. Furthermore, this model does not consider 3D visibility and overlooks the role of background expectations during directed wayfinding.

With regards to 3D visual perception, multilevel building complexity is decomposed into isolated 2D graph representations of each floor, although agents' movement is often visualized on a 3D building model. The main shortcoming of this approach is its inability to support 3D field of view calculations in a way that captures agents' visual perception in a multilevel space. A few notable exceptions simulate wayfinding using 3D visibility[19, 14], but these studies focus on wayfinding aided by signage perception using a 3D field of view.

More recently, Kielar et al developed Spice, a framework for cognitive-pedestrian modeling[11]. Spice's architecture combines the three-layered approach to pedestrian modeling with concepts from cognitive and social science. Agents' decision-making process is hierarchical and is informed by a 2D field of view and a 2D representation of an environment. Although Kielar's work is very much in-line with our aim of combining pedestrian modeling with cognitive principles, it does not take account of wayfinding towards non-visible goals and for 3D visual perception of multilevel spaces.

3 THE COGARCH SIMULATION FRAMEWORK

3.1 Overview

The development of cogARCH aims to overcome the limitations discussed above and simulate the process of unaided and directed wayfinding in unfamiliar, multilevel buildings. Achieving this requires both a cognitive agent model to represent human spatial search process and a navigation space to represent the building search space, and these must be both sufficient and complementary. To this end, cogARCH provides a computational framework in which a cognitive and parametric agent model interacts with a 3D, hierarchical and semantically rich navigation space generated from a BIM representation of a multilevel building.

cogARCH consists of three core modules: (1) spaces (2) agents, and (3) tasks. Simulation parameters are specified and controlled by (4) a batch simulator module or by a (5) GUI module that enables manual assignment of wayfinding scenarios and supports expert-based visual inspection of the simulation in real-time. Data collected during the simulation is stored in (6) a data collector module from which it is further analyzed and visualized using (7) analysis and visualization engine. The chosen development environment is Unity3D, a video-game engine that is able to support the physics and processing of complex geometries. Figure 1 provides an overview of cogARCH's framework structure.

3.2 Spaces

The navigation space in cogARCH is hierarchical. Each layer describes geometric, topological, semantic or metric properties of the building that are necessary to support agents' wayfinding decisions. Three interconnected layers are generated from the building description, imported as an IFC file from a BIM environment. The first layer consists of 3D convex zone partitions that discretize the building space into high-level path choices. Zones are created manually during the modeling of the building in a BIM environment. Zone boundaries are determined by two criteria: visibility and semantics. In contrast to purely continuous representations of navigation spaces such as those that discretize space uniformly into equal-sized cells, each of which is a unit of choice, the syntactical nature of zones allows similar and adjacent cells to be grouped semantically into meaningful units of spatial choice.

We distinguish two types of zone: (a) room-like zones, which are 'naturally' bounded in both horizontal and vertical dimensions by walls, floors, ceiling, doors, and other surfaces; and (b) open-area zones, which are spaces that are not directly bounded by a surface, but rather indirectly, by applying surface extension[17] in the horizontal and vertical dimensions. For example, a long corridor along a row of offices is subdivided into zones to reflect the variation in information continuity that results from the ability to look through office doors and towards office spaces. Accordingly, while moving from one zone to the next, new visual information is available. Transition points are thus located on the boundaries of zones. We refer to these locations as decision thresholds in which agents make local decisions and choose amongst alternative zones. Each zone stores features related to its semantics (e.g. office, public), objects (e.g. desk, chair), and connected thresholds.

The second layer of the navigation space builds upon the first to derive a threshold graph. This graph represents the topological relation between zones and thresholds. Whereas the first two layers represent high-level movement choices, the third layer provides low-level metric information to support operational movement (e.g. path calculation, obstacle avoidance).

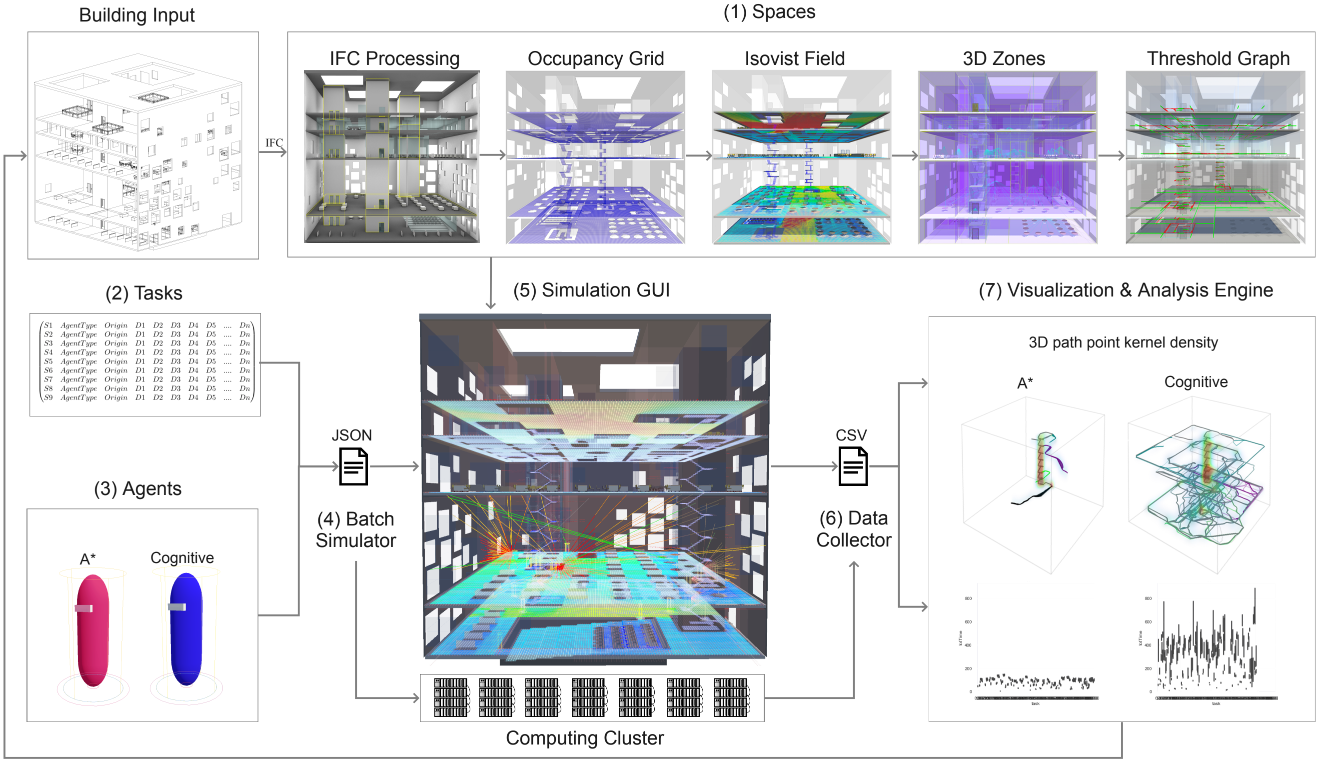


Figure 1: The cogARCH framework: A BIM model input is automatically processed into the layers of the hierarchical navigation space. Tasks and agent type are set using a batch simulator to execute simulations directly inside the GUI or remotely using a computing cluster. The simulation output is exported to a database for further analysis and visualization.

This layer consists of a multi-floor occupancy grid that provides a metric representation of walkable space. The occupancy grid graph is continuous along staircases without any need to link separate floors manually. The occupancy grid graph is also used to cast 2D isovists from each grid cell to form an isovist field. An area measure per isovist is calculated and mean isovist area for all cells within each zone is computed. The generation of the hierarchical navigation space is automated using a preprocessing pipeline. The output of preprocessing steps using this pipeline is visualized in Figure 1.

3.3 Agents

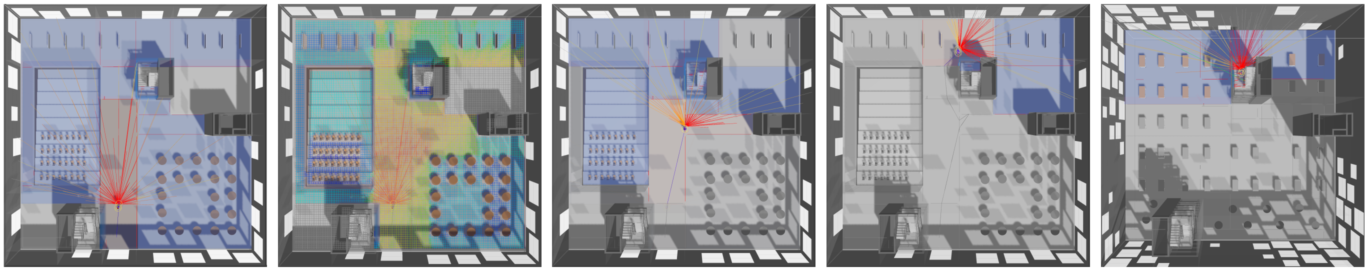
We assume that agents have no prior knowledge of the navigation space and that they are searching for a semantically defined destination, such as an office or entrance. Agents' template consists of the following four components: (1) a goal-specific expectation function (2) a 3D field of view (3) working memory, and (4) a state machine that represents the agent's decision-making process.

Similarly to the hierarchical navigation space described in the previous section, agents' wayfinding decisions follow a hierarchical structure from coarse to fine [10]. Three decision-making layers guide agents' wayfinding: (1) a strategic layer supports agents' ability to approximate the location of non-visible destinations; (2) a tactical layer allows agents to make local turn choices to move in the direction of the approximated destination; and (3) an operational layer allows agents to calculate an obstacle-free shortest path towards a visible target. The three layers composing the navigation space correspond to each of these decision-making layers. The strategic layer is informed by 3D zones, the tactical layer is supported by both 3D zones and the threshold graph, and the operational layer is supported by the occupancy grid.

An agent's access to each layer of the navigation space is bounded by its 3D visual field of view. At each decision threshold, an agent casts a 3D field of view and constructs a choice set of adjacent and visible zones and a set of zones that are only visible but not reachable in one time-step. This is critical for multilevel buildings in which potential goals could be visible, for instance. through atria, but are not directly accessible (e.g. because they are at another level).

To determine the approximate location of the destination, agents' strategic decision-making layer is in charge of ranking zone alternatives for expected cues according to its expectation function [5] or chosen wayfinding strategy [10, 3]. The wayfinding literature leads us to assume that agents would strive to maximize the correspondence between features of perceived zones and their goal-specific expectations or strategies. We thus formulate both expectations and strategies as a multi-objective optimization function per goal.

Instead of evaluating all zone alternatives for all possible features, a process that would require significant cognitive resources, agents apply the notion of heuristics to differentiate between alternative zones. Heuristics [6] are used to compare zone alternatives in a more human-like manner [6]. Accordingly, agents prune the number of alternative zones to only those satisfying distinct criteria. This heuristic follows the elimination-by-aspects theory of decision making. This the-



(a) T=1 (b) T=2 (c) T=6 (d) T=12 (e) T=23

Figure 2: Selected time steps showcasing a sample task performed by a cognitive agent in building scenario 2 (Glass): At T=1, the agent casts 3D field of view. At T=2 it evaluates zone alternatives based on destination expectations. The global goal is not visible so it ranks zones based on central point strategy using mean isovist area measure per zone. At T=6 the agent moves towards the threshold of the most integrated zone visible. At T=12 the agent doesn't gain new visibility information and the floor strategy is triggered. The agent moves to a visible zone with vertical circulation. At T=23 the agent moves up the staircase and during so perceives its global goal.

ory states that alternatives will be ignored if they do not fit within specific definitions of acceptability [21].

Algorithm 1: Agents' Decision-Making Process

Input: Agent's 2D and 3D perception of the environment
Output: Time history of agent's position and decision making

```
while Global Goal Is Not Visited do
    Cast 3D field of view;
    Log to Memory;
    Rank zones by expectation;
    if Global Goal is Visible then
        if Path is Visible then Follow Visible Path ;
        else if Path in Memory then
            Follow Path from Memory;
        else if Goal in same level then
            if NewRandomNumber $< 0.3$ then
                Rank zones by Direction Strategy;
            else Rank zones by Floor Strategy ;
        else Rank zones by Floor Strategy ;
    else Rank Zones by Central Point Strategy ;
    Set Local Goal Zone;
    Chose threshold;
    Find Shortest Path;
    Move to threshold;
end
```

Upon pruning the set of alternatives, agents aim to identify the highest ranked zone alternatives (i.e. that best match agents' expectations or strategy). This process is performed by ranking each zone for each relevant cue. If a zone matches all cues, the agent sets it as global goal, meaning the location of the final destination has been identified. If none of the zones meet agents' expectations, the agents rank the zones again for cues associated with the central point strategy. In this case, agents constrain their choices to public zones and aim to maximize mean isovist area per zone. Isovist area provides agents with a local measure of integration and is thus preferred over global measures such as visual graph connectivity.

Once a goal has been set, agents rely on their tactical decision-making layer to choose between visible zones that are also adjacent. If an agent is at the same floor as the goal, it may choose either the central point strategy or the direction strategy to rank adjacent zones. In the direction strategy, the agent strives to minimize the horizontal angle deviation towards the goal, thus choosing the zone that best meets this condition. If the agent is at a different floor from the goal, it can either perform the direction strategy or execute the floor strategy, in which it searches for an escalator, staircase, or elevator based on its expectation of vertical circulation cues. Once an adjacent zone has been chosen, the agent relies on its operational layer to calculate a shortest path using the A* algorithm and reach a threshold at a boundary with the adjacent zone.

This decision-making process repeats at every threshold until the agent finds its destination. Visited zones and thresholds are logged to construct a graph as part of the agents' working memory and allow the agent to follow a path from memory. The current stage of the framework's development does not incorporate angular distortion of stored locations or memorability on the basis of visual and semantic saliency. Additionally, a shortest-path agent using A* algorithm is implemented to simulate a benchmark shortest path and compare it against cognitive agents' paths.

3.4 Wayfinding Tasks

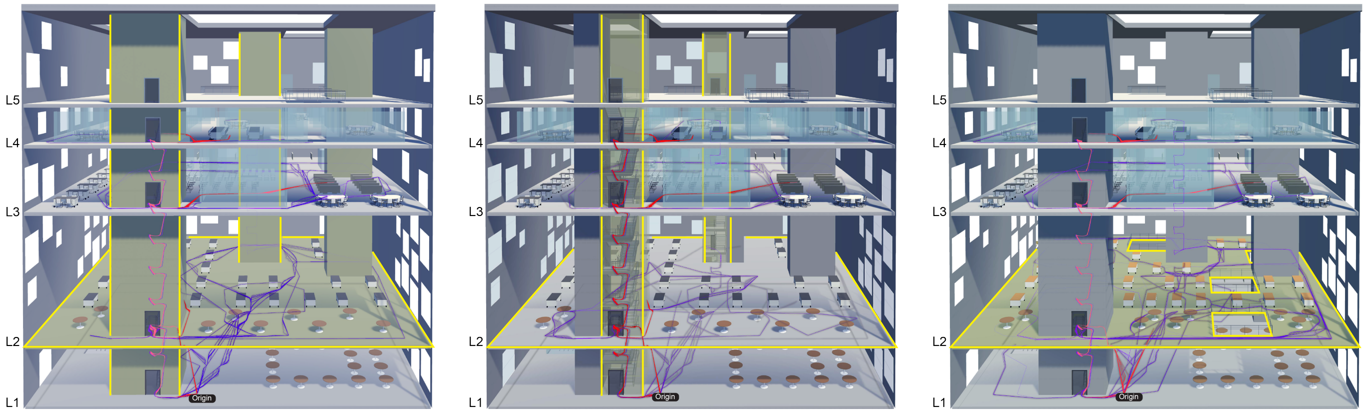
In cogARCH, wayfinding tasks consist of a single origin and either one or multiple destinations. Both origin and destination are defined by a zone rather than a point. Zones can be selected through direct interaction with the building model using the GUI or indirectly by specifying the semantics of destination zones: entrance, exit, staircase, elevator, or sitting area.

3.5 Simulation setup

Several parameters are used to define each simulation: (1) building scenario, (2) tasks, (3) type of agents performing each task, (4) the number of agents of each type to perform each task, and (5) the number of samples to be collected per scenario. The simulation parameters can be set either manually through the GUI, or with a text file in JSON format to specify all the simulation parameters. The second option is especially useful for supporting headless batch execution.

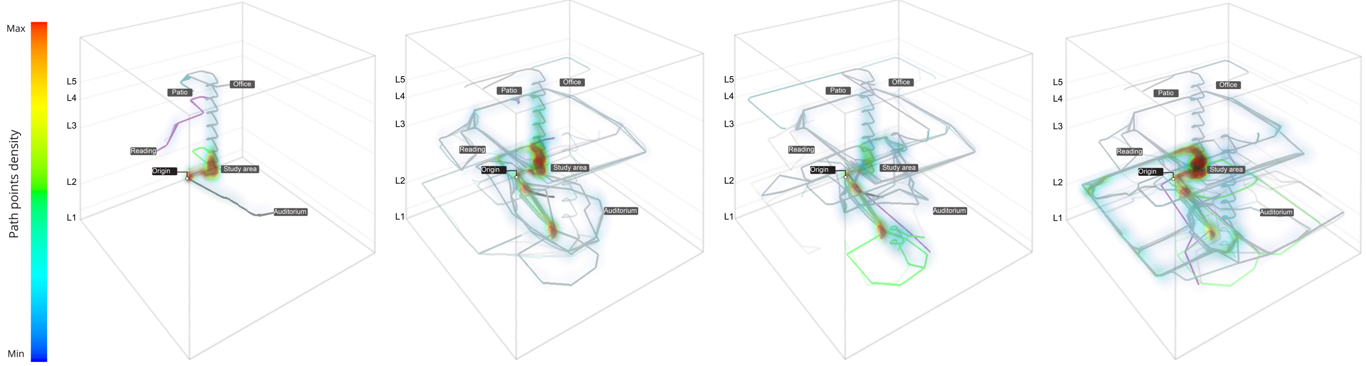
4 CASE STUDY RESULTS

To demonstrate the potential of cogARCH to architectural design, we apply it to evaluate variability in wayfinding performance across three multilevel building scenarios with systematically varied architectural design. Figure 3 shows 3D models



(a) Scenario 1: Base case (b) Scenario 2: Glass shafts (c) Scenario 3: Atria

Figure 3: Three building scenarios were evaluated. Scenario 1 is the base case building and the highlighted elements are those subject to variations. In Scenario 2, we apply material variation to the circulation shaft. Instead of a concrete enclosure, as in the base case, a glass facade is set. Scenario 3 presents a variation in floor permeability in the form of atria added to the second floor. Paths of both agent type for a subset of 5 tasks are included per scenario. (—, Shortest-path agent), (—, Cognitive agent)



(a) Shortest-path agents, across scenarios (b) Cognitive agents, Scenario 1.(Base -Case) (c) Cognitive agents, Scenario 2. (Glass shafts) (d) Cognitive agents, Scenario 3. (Atria)

Figure 4: Overlay of paths with 3D path point kernel density across 5 tasks for both agent types for each building scenario

	Building Scenario		
Agent Type	**1 (Base Case)**	**2 (Glass Shaft)**	**3 (Atria)**
Cognitive	10500	10500	10500
Shortest Path	10500	10500	10500

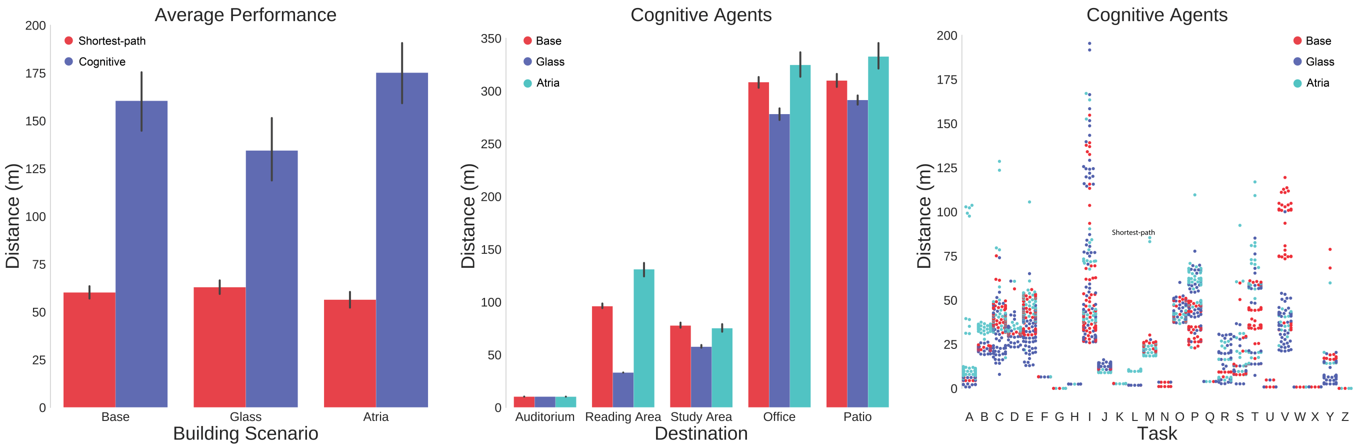
Table 1: The experimental setup used to conduct simulation experiments. 21 initial zones × 5 destinations × 100 samples =10500 samples in total per agent case pair. A total of 63000 samples

of all three building scenarios. The base-case building (Scenario 1) spans 5 building floors. The building program consists of a cafeteria, auditorium, exhibition space, open-space study areas, classrooms, office spaces, meeting rooms, indoor patios, and a roof terrace. Vertical circulation between floors is enabled by two staircases and two elevators located in enclosed concrete shafts. The building has two main entrances on the ground floor, located on opposing facades. Two variations to the base-case building are introduced. The first one, Scenario 2, replaces the concrete enclosure of both circulation shafts with a glass facade. The second variation, Scenario 3, introduces a series of small-scale atria on the second floor similar to those on the fifth floor.

Model	**Effect**	**Coef.**	**Std.Err.**	**z**
1 $dist \sim buil. + type$	buil. type	2.701 96.682	1.768 2.887	1.528 33.485
2 $dist \sim buil.$ S(B-G)	buil.	2.737	0.131	20.926
3 $dist \sim buil.$ C(B-G)	buil.	-26.323	1.487	-17.697
4 $dist \sim buil.$ S(B-A)	buil.	-3.781	0.385	-9.825
5 $dist \sim buil.$ C(B-A)	buil.	14.343	2.190	6.549

Table 2: Mixed Linear Model regression results of preliminary data

The proposed variations aim to make wayfinding in the base-case building more efficient by increasing vertical visibility between floors. Architectural changes are specifically applied to the three-dimensional configuration of the building. We do so to demonstrate the need for a cognitive agent with a 3D field of view in order to capture potential effects these variations may have on wayfinding performance and could not be observed using a shortest-path agent. Accordingly, we simulate both shortest-path and cognitive agents' wayfinding across typical tasks typical of novice occupants. These tasks consider 21 initial origin zones combined with one of 5 semantically defined destinations. A total of 63,000 samples is generated,



(a) Comparison of both agent types performance across building scenarios

(b) Cognitive agent performance across 5 typical wayfinding tasks across building scenarios

(c) Cognitive agent performance across 26 tasks across building scenarios

Figure 5: Comparison of simulated wayfinding performance across tasks, agents and building scenarios

see the experimental setup it Table 1. Monte Carlo type simulations were performed to evaluate the distribution of the results. Randomization has been introduced to agents' initial headings. The simulations were executed using a computing cluster through singularity-based containerization.

Preliminary results regard a subset of 5 tasks that origin from the buildings' main entrance. Figure 4 shows the difference in path dispersion using kernel density estimation. It can be observed that path density in shortest-path agents (see Figure 4a), is highly localized and shows minimal variability across scenarios in comparison to cognitive agents, (see Figures 4b,4c,4d). This results is further reflected when comparing average distance performance between cognitive and shortest-path agents across those 5 tasks Figure 5a. Whereas shortest-path agents showcase minimal performance variability, cognitive agents' performance varies largely between scenarios.

Given that distance performance varies across the 5 selected tasks (see Figure 5b), we provide further evidence through 5 Mixed Effects Model Regressions (MEMR) considering the wayfinding tasks as random effects, summarized in Table2. MEMR 1. models the building and agent type as fixed effects, and is evaluated across the subset of 5 wayfinding tasks. The model results show that the major effect across the entire sample is due to the agent type (an increase of 96.68m in the path lengths). All subsequent models evaluate individually either the shortest path agent (S) or the cognitive agent (C) against a pair of scenarios (i.e. Base vs Glass (B-G) or Base vs Atria considering only the building as the fixed effect. MEMR 2. shows that the architectural variation (Glass) has a marginal variation in shortest-path agents' performance and a minimal increase in the path length (2.737m); In contrast, MEMR 3. shows that this effect is substantial in the case of cognitive agents with an improvement of performance of (26.323m) from the base case scenario. Although MEMR 4 leads to the same observations as MEMR 2, it is interesting to notice that the effect of the atria (scenario 3) is actually a decrease of performance (14.343m) for the cognitive agents, meaning that agents covered more distance to find their way across tasks. Although this result could be counter-intuitive, it highlights the need for simulation tools such as cogARCH to inform architectural intuition with quantifiable metrics.

The presented sub-sample intends to show the potential of cogARCH to quantify the effects of architectural variations on wayfinding performance for a small-scale scenario that directly translate to a specific use-case (i.e. novice occupants). The rest of the results showcase cogARCH's ability to process larger data sets (e.g. from the 105 possible task we selected 26 named A through Z in Figure 5c). Figure 5c showcases mean distance covered by cognitive agents across 26 tasks for all three building scenarios. As can be seen, mean distance across tasks within samples from the same building scenario, as well as between scenarios, varies. In this case the analysis is unequivocal in favour of one building scenario with respect to our design objective (i.e. more efficient wayfinding). This finding reflects the complex nature of architectural design and the need for simulation tools to reveal potential performance tradeoffs that are not necessarily intuitive to predict otherwise.

5 CONCLUSION

The ability to foresee how architectural design decisions impact occupants' wayfinding can provide ample inspiration to inform design decisions and actively facilitate *wayfinding by architecture*. Multilevel buildings, with their multiple usages, complex three-dimensional configurations, and many origin and destination pairs, provide particular challenges that current simulation tools have not yet addressed.

This paper presented cogARCH, a computational simulation framework to evaluate wayfinding performance in multilevel buildings. Preliminary results have demonstrated cogARCH's capacity to capture significant variability in wayfinding behavior given architectural design variations applied to a 3D multilevel building. This finding stands in contrast to the significantly less varied wayfinding performance of shortest-path agents sampled under the same scenarios. Extending our work and validating our findings requires a validation protocol. To that end, a series of virtual-reality and real-world experiments is underway to replicate the behaviors simulated in cogARCH. By comparing observed behavior against simulated, the predictive power of our model will be assessed and the model adapted as necessary.

Future applications of cogARCH aim to extend its cognitive agent to deal with prior knowledge of the building and processes of knowledge acquisition. We further aspire to integrate other models of cognitive agents and to establish benchmark cases for assessing variability between models against real-world and lab-based data. Concurrently with extending cogARCH, we aspire to integrate it in simulation-based generative design workflows. Such integration would incorporate evaluation of wayfinding performance alongside other performance criteria to prune the solution space. Such an approach has the potential to introduce a much-needed occupant-centered perspective to future applications of architectural optimization and design automation.

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