Mental Models in Micro Worlds: Situated Representations for the Navigationally Challenged

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Abstract—In a navigation context, a mental model is defined as an internal representation employed to encode, predict, and evaluate the consequences of perceived and expected changes in the environment that result from both active planning and decision making as well as from external influences. A model is proposed to capture how human navigators dynamically represent the world to accomplish goal directed navigation tasks. This situated representation scheme not only embodies multi-granular notions of location and orientation, but also the ability to learn from observations and active exploration. The computational framework for this situated representation is based on evidence theory.

1. Introduction

The active navigation framework presented herein sets the stage for extensive micro-world experimentation. Our goal is to experimentally explore the structure, acquisition and application of mental models used to navigate through a city using different micro-world environments[1]. We are particularly interested in how people's navigational strategies are affected by: (a) the task and goal definitions, (b) their mental models, and (c) the use of navigation devices that provide information at different levels of specificity as well as with different degrees of reliability and accuracy. The proposed model of human navigation (with an eye toward spatial learning) presented herein offers a framework in which navigational information from many sources can be combined in a cognitively plausible way. It ties together three pillars of navigation: knowledge representation, information processing, and decision making. In this paper, we propose a computational framework of a navigator's mental model. We call the framework a situated representation and employ evidence theory for computational modeling of this framework.

Dempster-Shafer evidence theory provides the cognitive plausibility, the compositional richness and the modeling flexibility we need to formalize the relevant aspects of navigational representation [11,7]. It provides a multi-resolutional formalism for modeling the situated representation. It offers a means to characterize the content and dynamics of a navigator's representation of an environment, as well as a means to integrate subjective information provided by the environment and locomotion itself. The ultimate representation of an environment is likened to the London Taxi-Cab's notion of "The Knowledge".

We define L^3*-navigation* as the process by which people acquire knowledge about the *Layout* of an environment, rules about how *Landmarks* can be used to guide behavior, and the skill to *Locomote* through the environment. These three levels correspond to Rasmussen's knowledge, rule and skill based behavior (KRS) of people's interaction with a system or environment [10]. The goal is to find, using driving simulator experiments, the proper stimuli to elicit behavioral signatures that can be used not only to determine to what degree people's mental models have developed at each of these levels, but also to identify the mental model content.

The level at which a person can think about the task of finding a destination is also (a) the level at which people can best be instructed or informed about reaching the destination, and (b) the level people actively use in getting to their destination. In other words, there are levels of *representation*, levels of *instructions*, and levels of *interaction* that nicely map onto the KRS structure. At the *Layout* level, one can think about the city as a city, as a collection of spatially organized regions (e.g. suburbs), or as a street network of a particular topology (e.g. a grid), each with its own characteristic set of attributes (e.g. architectural style of housing in a particular region) which aid recognition and localization. At the *Landmark* level, one can think about a landmark's utility to be differentiated in terms of its localizing, orienting and decision making support. At the *Locomotion* level, an interesting distinction can be made in terms of reference frame, namely ego- or exo-centered; the particular frame choice may depend, for example, on whether active navigation, or route planning is involved.

L^3*-navigation* is assumed to be mediated by E^3*-learning* which consists of learning by *Exploration*, by *Example*, or by *Education*. The distinction between example and education is that someone shows the way in the former and instructs about the way in the latter. Exploration refers to a navigators active probing of the environment's connectivity structure. Landmarks can be thought of as instructors especially when encoded as choice points [5].

A driver's mental model aids in problem solving. It offers answers to questions such as: "where am I", "which direction am I going", "how close am I to my destination", or "where do I need to turn to reach some location or area that gets me closer to my destination". These questions tap into the different levels in the abstraction hierarchy (granularity) of both how to describe a city as well as how to navigate a city (which may be very distinct).

2. Behavioral Way-Finding Model

Computational Process Modeling of spatial cognition and behavior generally implements psychological processes through rules that act on symbolic representations of spatial information [e.g. 6]. Most artificial intelligence based models focus on the knowledge

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[1] A micro-world environment is a reality resembling task environment in which much of the complexity is preserved but is more easily manipulated than the real world. These micro-worlds offer a means to study naturalistic decision making.

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representation and do not include how people use them in active navigation; they ignore skill and the dynamics of navigational knowledge (i.e. posses no situated intelligence) [3]. In [9] the navigating cognitive system as a whole is viewed as a synergistic self-organizing system, the dynamics of which is an ongoing interaction between internal and external elements. Intermediate to these modeling approaches, we introduce a behavior generating multi-resolutional model using Demster-Shafer evidence theory to represent and operationalize a navigator's navigational knowledge. The focus in this paper is on representation. Some of the mechanisms involved in updating a navigator's knowledge when new evidence is actively obtained are discussed.

2.1 Representation

Humans represent space in a multitude of ways ranging from world-centered to ego-centered, and from veridical maps to collections of action specific landmarks. Without any representation, goal directed or task specific navigation skill looses meaning. Similarly, without the skill to navigate (e.g. move around, access information sources), a representation is mostly a static entity. We therefore tie representation and action together in a dynamic modeling framework that offers support to a navigating decision maker.

People's navigational or cognitive maps generally include representations about landmarks[2], specific routes and survey knowledge [5]. Others have made the distinction in terms of visually versus spatially dominated strategies to solve route learning problems [1]. Our model offers the flexibility to produce each of these representations or behaviors by differentiating the manner in which new evidence is integrated into the existing knowledge structure (representation), as well as by the manner in which the existing knowledge structure is used in planning and decision making. Here we focus on representation

We model people's spatial knowledge as a multi-resolutional belief structure in which different resolution levels correspond to different levels of spatial and connective granularity. This means that one can think about a city at the level of districts, as well as in terms of streets and intersections. The level of representational details depends on why and how it is used. The different levels of representational granularity are closely related to Moray's notion of lattices [8]: many to one mappings that indicate the connectivity between the different mental models that people may use in interacting with a system (e.g. navigating through a city).

2.2 Role of Landmarks

Landmarks can be divided into local and global. They may trigger both recollection of local connectivity maps as well as actions to help achieve the goal at hand [5]. In general terms, recognized landmarks offer evidence[3] for location and/or bearing; and they may act as local decision triggers. A few examples of local landmarks are: a building, the number of streets converging into or diverging from an intersection, and configuration of street connectivity (informational strength depends to some degree on viewpoint). A few examples of global landmarks are: mountains to the west, ocean to the west, and a central north-south freeway. The location and bearing state variables can be defined in relative terms (e.g. with respect to a destination or other more salient landmark) or absolute terms (e.g. global landmarks or geographic constants such as north).

2.3 Interaction with the Environment

The navigator's representation of the environment allows it to reason about its current knowledge of its location/orientation state, and use it to guide planning and decision making. The questions it can reasonably ask are exactly those that mental models are often associated with. They can be divided into the classes of *expectation*, *confirmation* and *exploration*. An example of each respectively is: "If I do this then I expect that", "When I see this I know that", and "If I do this, I don't know where it will lead me; bit I reach something I recognize, then I learned something about the city's topology".

The granularity of a navigator's active representation of the environment's connectivity structure depends to a large degree on its purpose at any instance. It may, for example, be highly detailed for the immediate surroundings and much coarser for distant areas. It may also depend on the navigator's proximity to a (sub-)goal destination. For example, details about how to get through a particular area may not be important as long as the general direction is maintained. Whether this knowledge is always accessible at all levels of granularity or whether it gains detail as one enters a particular behavioral domain remains to be explored experimentally.

Coarse representational knowledge is reflected by the size of the subsets (i.e. regions in the city). Certainty about connectivity between subsets can be directly linked to observations or can be thought of as computed (deduced) from finer connectivity maps[4]. Having strong belief about being in a particular location in the environment at one level (e.g. a particular district) does not mean that anything concrete can be concluded about its subsets or supersets. That this is true for subsets should be immediately clear since, for example, knowing I am in a particular part of a city does not necessarily say anything about which street or intersection I am at. Going up in the hierarchy has a much more semantic flavor in that knowing I am on a particular street does not necessarily mean I know the name of the area, or may only help me know I am in one of two townships.

3. The Model's Theoretical Details

The navigator's (*N's*) knowledge about the environment (*E's*) includes three components: whereabouts, topology, and landmarks. *N's* knowledge about its whereabouts is represented in the form of an orientational belief structure $\left\{m_k(i) : i \in 2^X\right\}$ (Section 3.1.3). *N's* knowledge about the city's topology (connectivity) is represented in the form of a belief lattice $\left\{\left\{\widetilde{w}_{T(i,j)}(A)\right\} : \forall i, j, A \in 2^{X^c}\right\}$ (Section 3.1.4). Landmark knowledge is represented in the form three belief structures

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[2] People with primarily landmark or choice point navigational knowledge encode what to do at a choice point. They may not have, need, or use any connectivity information encoded in a survey representation.

[3] We purposefully use the term "offer" here to highlight that the navigator may not perceive the landmark for a number of reasons such as other important features, lack of expectation, and insufficient scanning time.

[4] The computational aspects is merely a matter of combining all the belief structures that signify the existence of a link between a member of one set and a member of the other set; the notion of belief structures is explained in Section 3.

$\left\{\left\{\tilde{w}^l_{L(n)}(A): A \in 2^{X^l}\right\}, \left\{\tilde{w}^b_{L(n)}(A): A \in 2^{X^b}\right\}, \left\{\tilde{w}^a_{L(n)}(A): A \in 2^{X^a}\right\}\right\}$ (Section 3.1.5). The interaction between these representations is discussed including initial ideas on update rules are presented in Section 3.2.

3.1 Representation and Notation

We first introduce the notational structure surrounding the representation of a *N's* whereabouts; i.e. the belief structure. Subsequently we talk about *N's* topological representation of the environment; i.e. a belief net in the form of a weighted graph with transition matrix *T*. Finally, we discuss the representation of landmarks in terms of their support values.

3.1.1 Dempster-Shafer Evidence Theory

N's total amount of belief (mass) in a particular knowledge domain that can be assigned to the different possible propositions x equals one (i.e. belief is limited to indicate that one can not believe in everything[5]). The portion assigned to a particular x (which can be as small as an elementary proposition) of a navigator's total mass of belief is denoted with $m(x)$, where $m(.)$ is the *basic probability assignment function*. This measure has to satisfy the following axioms [7]:

I. $m(i) \geq 0, \forall i \in 2^X$

II. $m(\emptyset) = 0$

III. $\sum_{i \in 2^X} m(i) = 1$

where the set of all possible propositions x corresponds to the frame of discernment X in evidence theory. It represents all there is to know. The power set 2^X of X is the set of all possible sets of proposition. The collection $\{m(x): x \in 2^X\}$ is called a belief structure. Subsequent sections provide further intuition about these notions as well as their application to knowledge representation.

To allow for sufficient modeling flexibility, a different belief structure is assigned to the three basic types of knowledge necessary in navigation; they are differentiated by superscripts: l for *location*, b for *bearing*[6], and a for *action*. This superscript applies to $m(.)$ as well as X. For example, $\{m^a_o(i): i \in 2^{X^a}\}$ is the belief structure derived from a particular observation dictating which action to take in the set of locations i by assigning a belief to each possible action. The same superscripts apply to *N's* knowledge, so that $\{m^b_k(i): i \in 2^{X^b}\}$ is *N's* current belief structure about its bearing. Note that 2^X covers all granularity levels.

Finally, in some cases, a second argument t is given to the *basic probability assignment function* to indicate the degree of belief at a particular time instance.

3.1.2 Whereabouts Knowledge

N's current belief structure regarding it's whereabouts or orientation $\{m_k(i): i \in 2^X\}$ is identified by subscript *'k'* for *knowledge*. The portion that N assigns to a particular region i (which can be as small as a singleton location) of its total mass of belief is denoted with $m_k(i)$. The degree of evidence obtained from an observation is captured in the belief structure $\{m_o(i): i \in 2^X\}$, which is identified by subscript 'o' for *observation*. In Section 3.2.1, we not only show how $\{m_o(i): i \in 2^X\}$ is obtained, but also how $\{m_o(i): i \in 2^X\}$ and $\{m_k(i): i \in 2^X\}$ are combined to update *N's* existing belief structure of its whereabouts.

3.1.3 Topological Knowledge

N's general knowledge about the *E's* topology is represented by a weighted graph with nodes and connecting edges. This graph is represented by a transition matrix T [4].

Each ***node*** in the graph represents a location. A node can be as local as an intersection or as global as the entire city; this means that multiple weighted graphs can be present simultaneously indicating the different levels at which N can think about and interact with E. These graphs may be linked vertically to signify knowledge transfer between different levels of representation [8].

Each ***edge*** represents a means to travel between two nodes such as a street or a set of streets. The weights on an edge represents the degree of recall belief $\tilde{w}_{T(i,j)}$ the navigator has about the existence of a connection between locations i and j. Again, note that i and j do not have to be singleton locations[7].

A connection is defined as a one step path between two locations, which can be defined at any level of granularity. For example, if I think about the environment on the level of singleton locations, then when I assert that location i and location j are connected, I mean that I can travel from i to j without passing through any other node in this level's (granularity) connectivity graph. Similarly, if I think about the greater Boston metropolitan area in terms of cities and I assert that a connection exists between Cambridge and Boston, all I mean is that there is not another city between the two or equivalently when I travel from on to the other I don't have to travel through any other cities. Note that a step at coarse granularity level can correspond to many steps at a fine granularity level.

Two types of knowledge are distinguished: *recall* and *recognition*.

Recall knowledge refers to *N's* ability to think about the environment without perceptual confirmation ("I know it regardless whether I see it or not"); the basic probability assignment function for each possible connection is denoted by $\tilde{w}_{T(i,j)}(A)$, which assigns a degree of belief to entry (i,j) in the transition matrix T of the weighted connectivity graph[8]. The frame of discernment for

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[5] One can belief in nothing (i.e. within the frame of discernment or knowledge domain) which basically means that one acknowledges that there is something to belief but that one is completely ignorant about what to belief.

[6] We use bearing because of its connotation regarding goal directed navigation. Note that bearing can be defined in reference of North as well as relative to a target. Orientation is often used to denote a navigator's location as well as heading or bearing.

[7] The ~ signifies the imaginary nature compared to the - which will be used to indicate the more direct perception based recognition.

[8] Higher levels of connectivity representation can be thought of as transition matrices in which certain rows and columns are combined to indicate sets of nodes and connection between these sets be representative of possibly multiple paths.

each connection is $X^{c}_{T(i,j)} = \{C, \neg C\}$ and $A \in 2^{X^{c}_{T(i,j)}}$, which means that the connection exists (*C*) or it doesn't ($\neg C$). *N* assigns a degree of belief to each A[9], which changes with experience and exposure. In short we have a belief structure on every possible connection whence a triplet $\left\{\tilde{w}_{T(i,j)}(C), \tilde{w}_{T(i,j)}(\neg C), \tilde{w}_{T(i,j)}(X)\right\}$ gets assigned to every entry in *T*. The whole is referred to as a belief lattice. This appears ambitious, but we are saved by the sparsity of *T* and the existence of connections between regions (sets) rather than points (singletons).

Certainty about the existence of a connection between two locations *i* and *j*, means that $\tilde{w}_{T(i,j)}(C) = 1$, $\tilde{w}_{T(i,j)}(\neg C) = 0$, and $\tilde{w}_{T(i,j)}(X) = 0$. This triplet also gets assigned to each diagonal entry in *T* by virtue of the necessity that one can get from a given location to the same location by simply staying put for one step.

Recognition knowledge refers to *N's* ability to interact with the environment via perceptual confirmation. This does not directly apply to the environment's topology since it does not require perception in the strongest sense of the word. Instead it applies to the representation of landmark knowledge discussed next.

3.1.4 Landmark Knowledge

Here we focus on the notational structure for *N's* representation of *E's* landmarks. Again, two types of knowledge are distinguished: *recall* and *recognition*. Unlike topological knowledge, landmarks are represented in terms of recall as well as recognition knowledge.

We can reason about a landmark in terms of its support for *location*, *bearing*, and *action*. Since all three are important for *N* in goal directed navigation, we assume these three types of information to be represented more or less independently[10]. Often we can reason about a landmark without seeing it, in which case we use recall knowledge. Other times they are merely recognized and utilized when seen. The former knowledge type is important in planning while the latter knowledge type suffices when guidance is all that is required as is often the case when we simply retrace steps taken earlier.

It is important to recognize that location, bearing and action information are linked to different frames of discernment. Examples for the three frames of discernment are: $X^{l} = \{x_{l}\}$ is the set of all singleton locations; $X^{b} = \{N, NE, E, SE, S, SW, W, NW\}$ which is more or less independent of the adopted granularity, is the set of all possible directions; and $X^{a} = \{\mathit{SoftLeft}, \mathit{Left}, \mathit{SharpLeft}, \mathit{SoftRight}, \mathit{Right}, \mathit{SharpRight}, \mathit{Straight}\}$ is the action based frame of discernment, which is closely tied to the possible actions that one can take at the current location[11].

At the moment we assume an exo-centered frame of discernment for location, bearing and action. In some tasks or situations an ego-centered or goal-centered reference may be more appropriate for all frames of discernment. The modeling framework we present offers the flexibility needed to tailor the knowledge structures to specific individuals or conditions.

Recognition knowledge refers to *N's* ability to interact with the environment via perceptual confirmation ("if I see it I know it", or "I know it when I see it"). Reasoning about a landmark via recall is generally more uncertain than via recognition, which implies that $\tilde{w}^{x}_{L(n)}(A) < \overline{w}^{x}_{L(n)}(A), x \in \{l, b, a\}$. The recognition and recall basic probability assignment function for a landmark's orienting utility are respectively denoted by $\overline{w}^{x}_{L(n)}(A)$ and $\tilde{w}^{x}_{L(n)}(A)$, where superscript $x \in \{l, b, a\}$. Omitting the recall/recognition distinction, the three different belief structures are as follows: $\left\{w^{l}_{L(n)}(i) : i \in 2^{X^{l}}\right\}$ is the degree of support landmark $L(n)$ offers in terms of being in location i[12], $\left\{w^{b}_{L(n)}(i) : i \in 2^{X^{b}}\right\}$ is the support for bearing, and $\left\{w^{a}_{L(n)}(i) : i \in 2^{X^{a}}\right\}$ is support for the relevant action to perform (i.e. landmark as a choice point[13]). In terms of a concrete example, $\overline{w}^{l}_{L(n)}(i)$ represents *N's* estimate of the degree of support that the recognized landmark $L(n)$ provides for being in location i[14].

In the current model, we assume that the appearance of a landmark is known and that only its location and usefulness are represented. Others have modeled the perceptual aspects associated with landmark usage; e.g. [6]. By only loosely coupling landmarks to the connectivity map, no restrictions are placed on the number of landmarks associated with a particular location nor on the level of granularity in the active connectivity graph (transition matrix).

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[9] This degree of belief is zero for either case which mean that $\tilde{w}_{T(i,j)}(X) = 1$, which means they are ignorant about that particular connection because they have never received any support about its existence or inexistence.

[10] Even though landmarks may provided task specific decision support, the same information can be deduced from *N's* knowledge structure. We think of these two approaches to navigation as falling on a continuum. For example, landmark knowledge becomes less important (may still be used however) when a very good survey representation has been acquired (i.e. connections with high degrees of belief).

[11] Even though one can think about the need for being able to represent action while thinking about the city in terms of regions, its primary use is at the finest level of locational granularity where it is closely tied to planning and decision making.

[12] Note that this differs from *N's* belief that $L(n)$ is in location *i* which denote by $\lambda_{L(n)}(i)$ but do not further discuss in this paper. Some landmarks, such as the sun, can not easily be tied to a location in the environment (as defined by the frame of discernment); e.g. $\lambda_{sun}(X) = 1$. The value of this evidence is directly coupled to $\tilde{w}_{L(n)}(i)$ which indicates *N's* belief about a landmark $L(n)$ actually being present at location i.

[13] A choice point with its recognized turning decision has only meaning if tied to a particular goal and this knowledge has been gathered during previous excursions or was obtained from some information source. Also note that the action support provided by a landmark depends not only on location but also whether the navigator has performed that task at hand before in which case planning may not be needed because the necessary action is remembered. If action support at a particular location is low, then the decision mechanism is activated to generate an appropriate action. These choice point landmarks basically offer a means to bypass the need of planning and decision making.

[14] Note that during planning, conditioning is involved in combing belief about the landmark's location and belief about its usefulness.

3.2 *Observation-Knowledge Interaction*

The interplay between knowledge and observation is spelled out in this section. Some initial ideas pertaining to the dynamics of representation are also provided.

The landmark $w_{L(n)}$ and connectivity $w_{T(i,j)}$ belief structures are more or less independent of the "whereabouts" belief structure (*m*). However, they are not decoupled because once *N* gains high support of being in a particular location, then any landmark associated with that location also gains a high degree of belief. This does not mean that it always remains that high since people forget and may need multiple encounters for landmark knowledge to be closely tied to being in a location (i.e. long and short term memory). Note the distinction between the two roles of a landmark: orienting and directing; although a landmark may not be but helpful in terms of accurate localization and orientation, it may provide good support for deciding which way to turn.

Personal and developmental differences in terms of representational preferences will have interesting consequences for the ultimate belief structure associated with the different types of navigational knowledge. For example, landmark people may remain completely ignorant about the topological structure of the environment. These differences come about in the process of deciding how obtained evidence is being used to update the various representations. We hypothesize this stage of information aggregation to be a good candidate to model personal differences which is topic of future research.

We believe the following process to be a reasonable scenario of the different stages in *N's* interaction with an environment. *N* perceives a landmark and recognizes it; this brings about various beliefs about its location and usefulness in terms of localizing, bearing and action support; it integrates this observation support m_o with its currently believed location $m_k(t)$ to derive an updated belief about its exact whereabouts $m_k(t+1)$; the current connectivity belief lattice is consulted in conjunction with landmark knowledge to evaluate the benefits and costs of taking a particular turn. The most appropriate one for the current goal or sub-goal is selected and committed to action.

Once new observation evidence $m_o(i,t)$ for being in a particular location *i* has been obtained[15], *N's* existing orientational belief structure $\left\{m_k(i,t):i \in 2^X\right\}$ is updated by combining this new evidence. For ease of exposition, we assume that the knowledge source from which $m_o(i,t)$ was derived is independent of the existing belief structure[16].

Two stages are distinguished: (a) an observational stage in which the evidence provided by the observation is represented in an observation belief structure $\left\{m_o(i):i \in 2^{X^l}\right\}$ (Section 3.2.2), and (b) using this observational belief structure to update *N's* current orientational belief structure $\left\{m_k(i,t):i \in 2^X\right\}$ to obtain $\left\{m_k(i,t+1):i \in 2^X\right\}$ which requires combing two belief structures (Section 3.2.1). We now discuss this observation and update sequence in reverse order.

3.2.1 *Update*

Given that we have the new observational belief structure $\left\{m_o^l(i,t):i \in 2^{X^l}\right\}$, we combine it with the current locational knowledge belief structure $\left\{m_k^l(i,t):i \in 2^{X^l}\right\}$ to obtain the updated representation of *N's* knowledge about its whereabouts $\left\{m_k^l(i,t+1):i \in 2^{X^l}\right\}$.

To combine belief structures, first we need to compute the *ground assignment function* q. This is accomplished by computing the desired belief structure $\left\{q^l(A,t): A \in 2^X\right\}$, the following function is used

$$q^l(A,t) = \sum_{A=i_1 \cap i_2} m_k^l(i_i,t), m_o^l(i_2,t)$$

where the sum is taken of all pairs of subsets (i_1,i_2) for which $A = i_1 \cap i_2$. For $\left\{q(A,t): A \in 2^X\right\}$ to represent a belief structure, it has to satisfy the three axioms in Section 3.1.1. This requires a combination rule that removes conflict from the resulting belief structure.

In some cases, $q^l(\varnothing,t) \neq 0$ which signifies a conflict. Several rules have been developed for resolving this conflict. We adopt Yager's combination rule [12], which regards any contradiction as coming from ignorance:

$$m_k^l(C,t+1) = q^l(C,t), C \neq \varnothing$$
$$m_k^l(C,t+1) = 0, C = \varnothing$$
$$m_k^l(X,t+1) = q^l(X,t) + q(\varnothing)$$

where *C* is any subset of locations. For an account on different combination rules plus their interpretation and shortcomings we refer to [7][17].

If an observation is made but no landmark is perceived, that means that $\left\{m_o^l(i) = 0, m_o^l(\neg i) = 0, m_o^l(X) = 1\right\}$ and it is easily seen that $\left\{m_k^l(i,t+1):i \in 2^{X^l}\right\}$ equals $\left\{m_k^l(i,t):i \in 2^{X^l}\right\}$.

3.2.2 *Observe*

In combing the existing knowledge belief structure regarding location and the new observational belief structures associated with the observed landmark $L(n)$, the first step is compute $m_o^l(i)$ for all $i \in 2^X$ to obtain the new observational location belief structure. A landmark provides evidence for being in a particular location and at the same time evidence for not being in a different location. Both depend on how well one knows the landmark and how certain one is that it is unique. If the landmark is not unique it can provide some degree of evidence to being in one of several locations.

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[15] The simplest cases is when new evidence is tied to a simple elementary location.

[16] We are currently exploring how expectations derived from the existing belief structure may affect the evidence provided by new information. In other words, the degree to which new information satisfies the formulated expectation affects its informational value.

[17] Baroni et al. have recognized the problem of existing evidence combination rules and propose a cognitively plausible uncertainty calculus [2]. We are currently exploring ways to incorporate their ideas.

We give the equations for locational support by the perceived landmark $L(n)$ but the same hold for the other types of support that landmarks provide (i.e. bearing and action[18]):

$$q_o^l(i,t) = m_k^l(i,t)\overline{w}_{L(n)}^l(i,t) + m_k^l(i,t)\overline{w}_{L(n)}^l(X,t) + m_k^l(X,t)\overline{w}_{L(n)}^l(i,t)$$

$$q_o^l(\neg i,t) = m_k^l(\neg i,t)\overline{w}_{L(n)}^l(\neg i,t) + m_k^l(\neg i,t)\overline{w}_{L(n)}^l(X,t) + m_k^l(X,t)\overline{w}_{L(n)}^l(\neg i,t)$$

$$q_o^l(X,t) = m_k^l(X,t)\overline{w}_{L(n)}^l(X,t)$$

$$q_o^l(\varnothing,t) = m_k^l(i,t)\overline{w}_{L(n)}^l(\neg i,t) + m_k^l(\neg i,t)\overline{w}_{L(n)}^l(i,t)$$

Again we employ Yager's rule to remove conflict[19] and to obtain the belief structure associated with the observational support provided by landmark $L(n)$:

$$m_o^l(C,t) = q_o^l(C,t), C \neq \varnothing$$

$$m_o^l(C,t) = 0, C = \varnothing$$

$$m_o^l(X,t) = q_o^l(X,t) + q_o^l(\varnothing,t)$$

where C is any subset of locations. Note that $m_o^l(X)$ represents the degree to which this newly obtained evidence from the observed landmark tells the navigator that it is still in the city[20]; the degree of ignorance pertaining to the current observation only depends on how salient it is with respect to *N's* existing knowledge store.

4. Future Work

When the navigator acts on a decision, several changes in its belief structure take place. Evidence for being in the previous location i decreases while evidence in support of being in the expected new location j increases[21]. Formulation of cognitively plausible update rules is an area of future research. A closely related area for further research is how $\overline{w}_{L(n)}^x$ and $\widetilde{w}_{L(n)}^x$ develop as N interacts with the environment.

The degree to which knowledge at different granularities is activated and utilized simultaneously is what we are currently exploring in Grid-City, a micro world in which subjects perform various navigational tasks in which different levels of support are provided and different levels of problems given to determine at what level(s) they are interacting with the city's road network.

5. Conclusions

Evidence theory was employed to develop a situated representation of navigational knowledge. It offers a framework in which the observational, representational and decisions making aspects important in navigation are combined. It captures how human navigators may represent the world and offers a framework to model goal directed decision making and strategy selection and tie it to their effect on a navigator's representation of the environment. We believe that the multi-granular notions of location and orientation, tied to the ability to learn an integrate landmarks and observations offers a modeling richness that will greatly benefit experimental exploration of the mechanisms and representations involved in the structure, acquisition and application of a human navigator's mental models.

6. References

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[18] Action support depends on whether the same or a very closely related (sub-)goal has been aimed for previously.

[19] This occurs, for example, when one belief to be in a particular location, but sees a landmark that one knows very certain to be in another location. This is exactly the kind of case where learning takes place which is current topic of active research.

[20] The belief structure associated with observing a particular landmark is organized such that whatever belief can not be committed to its alleged location is attributed to the mere fact that it has to be in the city somewhere. It is assumed that *N* is not imagining landmarks.

[21] We purposefully talk about expected because this precedes reaching the new location and making an observation. The observational step was discussed in the previous section and is also very important in reinforcement learning which we belief to offer a good representation of a navigator's navigational learning.