Cognitive Spatial Representations for Mobile Robots - Perspectives from a user study

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***Abstract*— Robots are rapidly evolving from factory work-horses to robot-companions. The future of robots, as our companions, is highly dependent on their ability to understand, interpret and represent the environment in an efficient and consistent fashion, in a way that is comprehensible to humans. The work presented here is oriented in this direction. It suggests a hierarchical concept oriented representation of space that is based on objects. This work attempts to provide a "cognitive" validation to the proposed representation and also looks into ways of enhancing it. This is done by means of an elaborate user study experiment. Analysis of the data obtained from the user study provides a human perspective to the robotics problem. This work also attempts to put forward a more generic methodology in order to develop such a representation, to be able to map the robots sensory information to increasingly abstract concepts that describe the semantics of the space the robot inhabits. The work itself is aimed at radically improving the degree of spatial awareness of state-of-the-art robot systems. Thus, the theme of the work is - representation for spatial cognition.**

I. Introduction & Related Work

The state-of-the-art in mobile robotics use representations that are suited solely to the task of robot navigation. Further, these are not human compatible and fail to encode much or most of the semantics in the environment. This leaves them with little scope for use in more complex and interactive tasks. This is also the reason that the level of spatial awareness in current robot systems is quite modest. The focus of this work is to address these deficiencies. In an attempt to address these issues, a probabilistic object graph based representation of space was proposed in [1]. This work was a pure engineering exercise demonstrated on a robot platform. The work reported here attempts to address the problem from a human perspective.

Increasingly intelligent robots are tending to be more-and-more socially interactive. In the future, intelligence and the ability to meaningfully communicate will be critically important factors determining the compatibility and acceptability of robots in our homes. Most works in mobile robotics have until now restricted themselves to navigation related problems. Thus, few works evaluate their concepts in human centered experiments. A recent work which attempted to understand the acceptability of robots among people through a user study is done in [2]. This work was done on the sidelines of [3], which was a recent large scale demonstration of the remarkable growth of personal and service robotics. The representation proposed in this work promises to enable robots to not only perform navigation related tasks but also to be more spatially aware and human-compatible machines that could inhabit our homes alongside us. With the rapid increase in the importance of human robot interaction, the need for evaluating the work through human centered experiments was felt necessary. Further, it was felt that such experiments could contribute positively to the enhancement of the work itself. With this view, an elaborate user study was conducted to understand human perception and representation of spaces. This report is a detailed review of the salient aspects of the study.

The representation suggested here takes inspiration from the way we believe humans represent space and also the notion of a hierarchical representation of space. Ref. [4] suggests one such hierarchy for environment modeling. In [5], Kuipers put forward a *Spatial Semantic Hierarchy* which models space in layers comprising respectively of sensorimotor, view-based, place-related and metric information. Since the introduction of the term *Cognitive Map* in Tolman's seminal work [6], many research efforts have attempted to understand and conceptualize a cognitive map. The most relevant works include those of Kuipers [7] and Yeap [8]. The former viewed the cognitive map as having five different kinds of information (topological, metric, routes, fixed features and observations) each with its own representation. Yeap et al. in [8], review prior research on *early cognitive mapping* and classify representations as being space based or object based. The approach proposed here attempts to take the best of both worlds.

II. Approach

This work attempts to find answers to questions such as - (1) What is meant by "cognitive", when applied to a mobile robot from an engineering perspective? (2) How can a robot form a "cognitive" probabilistic representation of space? (3) How "cognitive" is the proposed approach and (4) How can a robot understand and reason about places? It does not attempt to propose a new theory of the mind. It proposes a human compatible representation of space for mobile robots and attempts to evaluate / enhance it through the user study presented. The proposed approach is shown in figure 1. The principle idea is that by adding concepts (created for instance using the functionality of the underlying elements) to the representation, semantics can be embedded in a purely navigation oriented map. The result can be understood as a concept oriented representation of space.

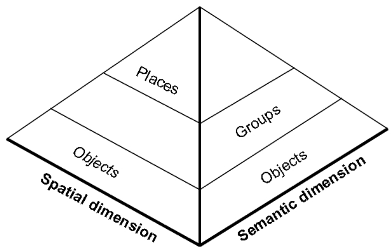

Fig. 1. The general approach - A robot uses the sensory information it perceives to identify high level features such as objects, doors etc. These objects are grouped into abstractions along two dimensions - spatial and semantic. Along the semantic dimension, objects are clustered into groups so as to capture the spatial semantics. Along the spatial dimension, places are formed as collections of groups of objects. Spatial abstractions are primarily perceptual or structural formations (occurrence of walls, doors etc.) whereas semantic or functional abstractions are primarily conceptual formations (similarity of purpose / functionality ; spatial arrangement). The representation is a single hierarchy composed of sensory information being mapped to increasingly abstract concepts.

The described approach has been partially implemented on a robot platform. The detailed approach is elicited in [1]. The perception system included methods for object recognition and door detection. The representation was probabilistic in order to account for the uncertainty and incompleteness of perception. Knowing the robots pose (using odometry) relative to a local reference, the detected objects and doors were identified in the local frame of reference. Using this information, a probabilistic graphical representation encoding the objects and the relative spatial information between them was formed as a local representation for the place. The local representations of different places were connected through the doors that connect them. Spatial Cognition was demonstrated through experiments on place classification and place recognition. More recently, promising results have also been obtained on the formation of concepts or groups; these will be reported very shortly.

III. The study

A. Overview

The survey comprised of a questionnaire posed to fifty-two people who were taken through a course in our premises wherein they were exposed to day-to-day objects and places. Due to the geographical location of this work (Lausanne, Switzerland), questions were posed in English or French, as the user preferred. The questions were based on the model presented in fig. 1. The survey was intended to be as unbiased as possible, without loosing the focus of the work itself. It was also attempted to make it as statistically representative as possible. Care was taken to ensure, to the extent possible, that age, gender, nationality and vocational background did not bias the survey in any way. However, expectedly, a majority of the survey takers were either Swiss or French. In the following subsections, various parts of the study are detailed, the results visualized and their implications analyzed. The graphs also provide some examples of replies that were obtained. Ref. [9] is a more explanatory version of this document with photographs of the various areas and objects used for the study as well as the questionnaire used.

B. Objects

1) Representation: Users were asked to imagine and describe how they represent typical objects such as a chair and a cup. The means of representation of a chair is shown in fig. 2. It was found that the structure was the dominant aspect of the representation. Few people actually used the functional description of a chair - an object on which people can sit. The material composition of the chair was a relatively more significant factor. A lot of finer detail was also obtained. These have been classified in fig. 3. Here it was found that the type of a chair and the level of comfort it offered were the relatively significant aspects of such descriptions.

With regards to the cup, most users seemed to use a structure based internal representation, as shown in fig. 4. Here also, the material composition of the cup was at an intermediate level of significance between the structure and the function. The finer details that accompanied the description, shown in figure 5, included more information on the shape and size of the cup.

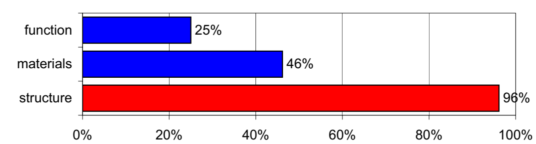

Fig. 2. Means of representation of a chair. Structure = { 4 legs, a seat, a back }, Materials = { wood, steel, plastic }, Function = { an object to sit on }

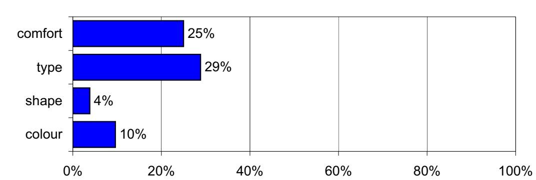

Fig. 3. Additional details used to represent a chair. Color = { brown, decorative patterns, black, dark } , Shape = { cubic shape, symmetric shape }, type = { kitchen chair, office chair } and comfort = { flexible, comfortable, rigid, cushioned }

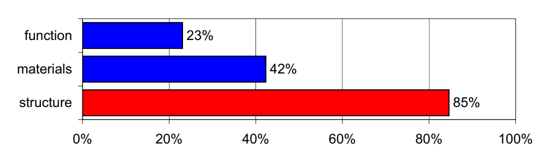

Fig. 4. Means of representation of a cup. Structure = { hollow object, container, handle }, Materials = { porcelain, ceramic, glass }, Function = { an object to contain or drink liquids }

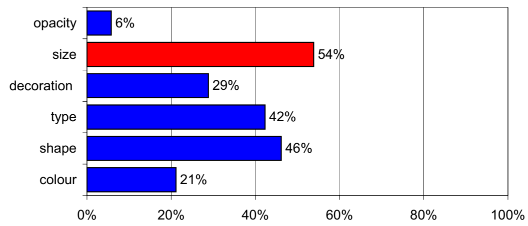

Fig. 5. Additional details used to represent a cup. Color = { white, plain color } , Shape = { cylindrical, round, oval, square }, type = { coffee cup, tea cup, espresso cup }, decoration = { patterns, text }, size = {various sizes, 0.5 l, 25-35 dl, 12 cm high and 67 cm in diameter }, opacity = { opaque }

2) Description of objects: In this part of the study, users were asked to observe and describe three objects - a traditional / simple chair, an office chair and a cup. The obtained descriptions were categorized as before. The means of description of the three objects are respectively depicted in figures 6, 8 and 10. The finer details of the description were also categorized and are depicted in figures 7, 9 and 11 respectively.

In the case of the office chair, the structure was the most important element describing it, followed by the type and the material composition of it. The finer detail obtained were primarily on the color and the comfort level that the chair offered. In comparison to this, while the structure of simple chairs was indeed the most important element, the significance between the remaining two factors was reversed. Also, the finer detail reflected more on the condition and the comfort level offered by the chair than its color. This is explainable since the traditional / simple chair used in this experiment is not particularly colorful or artistic, further it can be used in many different contexts and hence its *type* is indistinctive. The cup description also saw the greater significance of the structure over the type and the material composition. The finer detail of the cup was mostly concentrated on the decoration on the cup, its condition and size.

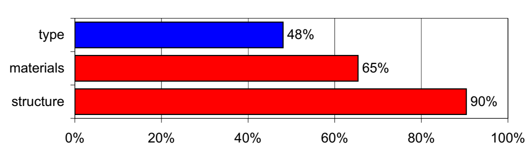

Fig. 6. Means of description of a simple chair. Structure = { 4 legs, a seat and a back}, Materials = { wood, steel, metal }, Type = { kitchen chair , school chair}

3) Object Recognition: Within the framework of these experiments, people were also queried on how they recognized typical objects. Their response was studied. Figure 12 shows the results of categorizing their answers. It was evident that most people used structural elements to identify objects.

4) Object arrangement: People were asked to describe a given scene (cupboard with objects above it and on its

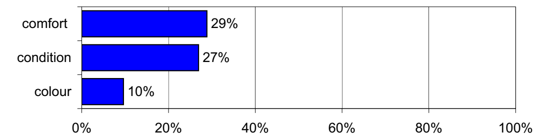

Fig. 7. Finer details in the description of a simple chair. Color = { brown }, Condition = { excessively used, dirty, slightly old }, comfort = { rigid, uncomfortable }

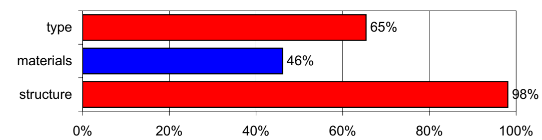

Fig. 8. Means of description of an office chair. Structure = { seat, back, axis with 5 wheels that roll }, Materials = { plastic, steel }, Type = { office chair, arm chair }

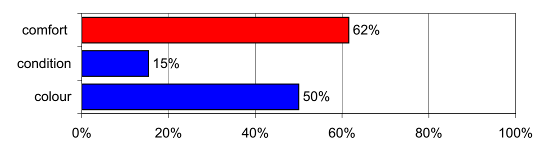

Fig. 9. Finer details in the description of a office chair. Color = { green, dark, colorful, decorative patterns on the cushion }, condition = { old, clean, nice }, comfort = { comfortable, ergonomic, adjustable }

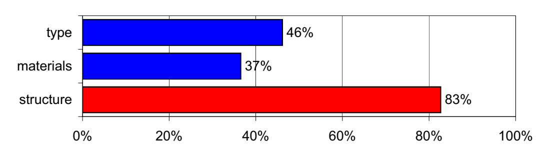

Fig. 10. Means of description of a cup. Structure = { cylinder with open top, hollow object, handle }, materials = { ceramic, porcelain }, type = { coffee cup, tea cup }

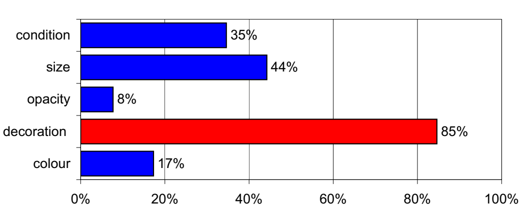

Fig. 11. Finer details in the description of a cup. Color = { white }, decoration = { picture of a dog and cat, gray background }, opacity = { not transparent }, size = { big, normal sized, 20 cl, 10-12 cm high }, condition = { used, stained, dirty, good condition }

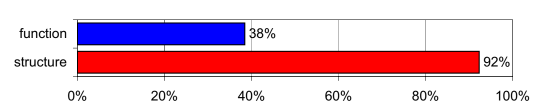

Fig. 12. Means of object recognition. Structure refers to the physical elements that make up the object whereas function refers to the more semantic aspects - functionalities of the object.

sides) in the refreshment room. Their response was studied. As shown in figure 13, people generally preferred to describe the scene from one end to the other (left to right or right to left) or in relation to a centralized object.

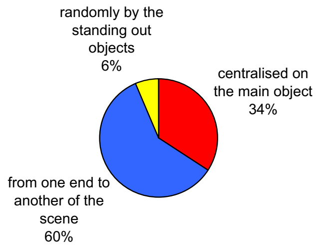

Fig. 13. Means of object arrangements in space

5) Analysis: The following summarizes the important observations made in the part of the study conducted above.

- The structure was the most prominent representative element for objects. This was followed by the material composition of the object.
- Descriptions of objects were also typically dominated by the structural information. However, the *type* of an object was found to be very relevant in this context. Similar but not the same as the *functionality* of an object, the *type* referred to the typical scenario in which the object was used.
- In both representation as well as description of objects, a lot of extra details were obtained, this could serve to enrich the proposed representation.
- Structure seemed to be the most important element in recognizing objects.
- Most people described the spatial configuration of a set of objects in an end-to-end fashion or less significantly, with respect to the central object.

C. Categorization

This part of the study aimed at understanding how people cluster and categorize space. The hypothesis under consideration was that people form explicit and implicit clusters of objects. This part of the study was aimed at understanding if the hypothesis is true, what were the basis of such clusters etc. Users were queried in different sized and featured environments about the existence of such clusters.

1) The Entrance Hall: People were taken first to an entrance hall of a building. As is usually the case, this was equipped with sofas, a telephone booth, some plants and some other tables and chairs. People were first asked to identify different zones [1] they observed and were then asked to justify their decision. The various zones that were formed in the entrance hall and the reasons for which they were formed are depicted in figures 14 and 15 respectively. Zones were mostly formed using groupings of objects and also due to the boundary elements. Typical zones identified as a result of grouping objects include a waiting zone (sofas, coffee table, plant etc.), phone zone (phone, chair, plant etc.), meeting zone(table and four chairs) and so on. Areas such as those near the entrance, in the corridor and near the stairs were identified as separate zones apparently due to the existence of boundary elements such as the walls, doors and the stairs. The meeting zone was sometimes identified by the objects composing it and at some other instances also included the boundary elements such as the window and the section of the stairs. Almost no-one used size as a metric to decide the existence of a zone. Further, it was found that objects were most often grouped due to the spatial arrangement they exhibited (for instance 4 chairs around a table) or due to the functionality they characterized or less significantly, due to the materials they were composed of.

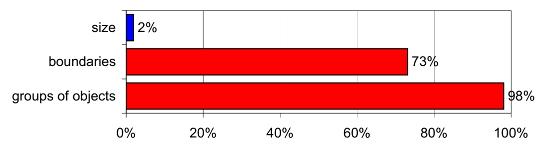

Fig. 14. Means of zone definition in entrance hall.

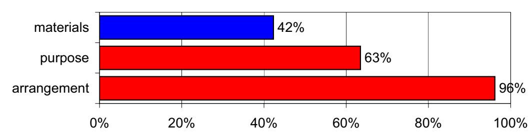

Fig. 15. Means of grouping objects in entrance hall

2) Laboratory / Office: People were next taken to a large laboratory-office. This room had 3 major areas within it - one part being a laboratory space with a lot of electronics and related lab-ware; the other part being meant for the people to work there and finally there was also a small round-table meeting area. As before, people were asked to identify if they saw any zones, if yes - which ones and why did they think that it was a zone? The results, when categorized appeared as shown in figure 16. In the case of every subject who took part in this study, the lab-office seemed to have 3 major zones within it. These zones were almost always identified by the objects lying around as the lab area (small electronic workshop) of the room looks significantly different to the office area (typical office). The objects clearly made out the zones. Many people also found the boundary elements within the room (partitions and an artificial wall made of cupboards) significant in that they separated the different zones. However, the general idea gathered from the study was that for most people, while the objects clearly grouped into 3 distinct regions within the room, the boundary elements were also useful but less significant and not absolutely necessary towards reaching this conclusion. Most often, the boundary elements were more supportive and less critical in the formation of the zones in this place.

3) Refreshment room: As in the previous case, people were taken to a refreshment room and asked to identify

[1] Refer section III-C.5 for details on the word *zone*

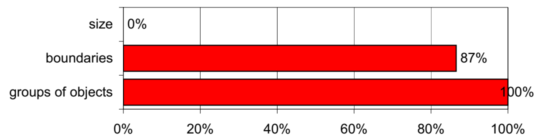

Fig. 16. Means of zone definition in a laboratory

zones within it. It is a relatively small room with a lot of diverse objects packed within it. The reasons for forming various zones in the refreshment room are illustrated in figure 17. The zones were almost always identified as a result of groupings of objects and both size and boundary elements were insignificant. The typical zones formed included a relaxing zone which comprised of objects like the sofas, the table and the surrounding plants, the kitchen zone which was the area having the coffee machine, kettle, microwave etc. and finally a book / storage / cupboard zone which housed a small library of books and archives of various technical journals and magazines. This was a case where object groupings were critical to the zone formation. Most people grouped objects due to their spatial arrangements and similarity of functionality / purpose. The rare exceptions included people who defined an entry zone based on the existence of a boundary element such as the door. Few people also viewed the whole room as a single place as they associated the three main functions of relaxing, eating / drinking and reading books as those that are common to a single place - i.e. they identified the 3 functionalities and felt that these were linked together and did not wish to identify them as separate zones.

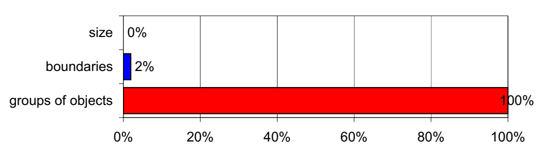

Fig. 17. Means of zone definition in a refreshment room

4) Office: Next, the users were taken to a typical office setting with three back-to-back/side tables a few cupboards and a table with a small experimental platform. As before, users were queried on the zones they could identify and the reasons why they did so. The results are depicted in figure 18, 19.

The office was a reasonably large room. Every single subject in the study identified the work place as a separate zone. This basically comprised of the three tables, chairs and work related objects that were on them. Many people also recognized the cupboards and shelf against the walls as a storage space. A few people seemed to perceive the existence of some experimental / robot hardware on a table as being a place for conducting experiments. A similar number of people perceived a separate zone just after the door and before the area containing the work related apparatus - this was termed as an entry space. A small number of people insisted on defining some sort of transition space between the entry space and the work place. What was particularly vindicating was that all the subjects formed zones through the grouping of objects and that the spatial arrangement of objects and their purpose were the two most contributing causes towards their being associated together to form the zone. A further experiment was also conducted in this place, the users were asked to explicitly cluster objects in the office. This resulted in users typically ending up reducing the grouping problem to that of a *classification of different kinds of objects* problem.

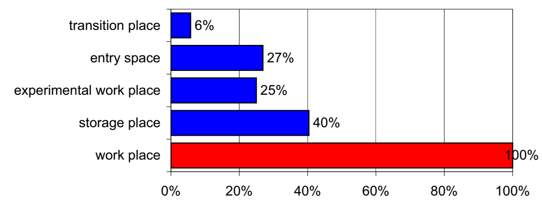

Fig. 18. Zone definition in an office

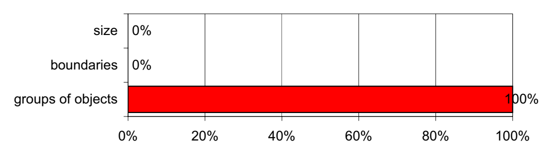

Fig. 19. Means of zone definition in an office

5) Analysis: The following conclusions could be drawn as a result of the experiments conducted in this subsection

- *On the word "zone"* - The word "zone" was used in order to avoid directly asking the user if they formed clusters and also taking into consideration local comprehensibility issues. The positive effect of framing the question this way was that user opinions were unbiased, yet they were not asked questions which they could not understand. The not-so-positive aspect of using this term was that people understood differently in different instances and replied with answers that had a mix of spatial and semantic abstractions. Users seemed to have understood a "zone" as being a standalone, separable unit, which was not quite what the survey designers wanted to convey. This made data analysis harder but nevertheless useful.
- *On the zones perceived* - People formed zones in the entrance hall - these were formed due to both object groupings and boundary elements such as the stairs that partition the entrance hall area. In the laboratory-office, it was observed that people were able to identify three separate zones even without partitions. The partitions of course, made this a more direct outcome. The refreshment room, being smaller in size, had only groupings of objects. The office also gave rise to zones - some were clear groupings of objects while some others such

as "entry space" and "transition space" had no obvious reason except the existence of a space that had a certain size and that clearly separated the user from a zone that had a certain clear and different semantics attached to it. Broadly, it was pointed out that there were two kinds of abstractions that were being produced - spatial and semantic (which are also termed as groups in this report). They are referred to here as semantic / functional abstractions (groups) and spatial abstractions (places). Semantic abstractions were almost always formed as a result of clustering objects - this clustering was typically the result of commonality in purpose and/or material composition, or specific spatial arrangements. Spatial abstractions were typically formed as a result of size and spatial elements such as doors, walls and partition elements. The exact effect of the former was clearly not well understood in this study and is being considered for future work. However, it was clear that intermediate level spatial abstractions (such as a small portion of a room partitioned off from the rest of the room, as in the case of the laboratory-office) were formed only when the size was significantly large. The presence of partitions led to the formation of a zone which is understood as an intermediate level spatial abstraction (or a mini-place of some sort within the place itself).

- *On the containment of semantic abstractions within spatial abstractions* - Given both spatial and semantic abstractions, there are two options on the hierarchy design - (1) to have both spatial and semantic abstractions at the same level of a hierarchy or (2) having a spatial abstraction contain a semantic one. In an office and in the refreshment room, there were quite a few people who, although identifying the existence of multiple functional areas (what are called semantic abstractions or groups here), did not want to split the room (a place) itself into those areas as they believed that these functional areas were an integral part of the same place. This fact seems to implicitly suggest the containment of semantic abstractions within the spatial abstractions. This seems intuitive, definitely valid for indoor environments and computationally suitable but probably could be more explicitly demonstrated. Thus, currently, as a design decision, spatial abstractions are chosen to contain semantic ones. However, proving/disproving this in a more explicit manner is something that should be addressed in future work.
- *On size dependence* - There is a clear dependence of size on the formation of zones. This was indicated in the lab-office and in the entrance hall. However this has not been explicitly addressed as this was a realization of the experiments themselves and the survey could not be modified at an intermediate stage. This would also be considered in the context of future work.

D. Places

The objective of this part of the study was to understand how people perceive different places. The working hypothesis here was that of an object based representation of space.

1) Representation: In this exercise, people were asked to imagine themselves in a place, such as a kitchen or an office. They were then asked to describe their perception in as much detail as they possibly could. The means of representing an office, a living room and a kitchen are respectively shown in figures 20, 21 and 22. Clearly objects and boundary elements formed the core of the replies obtained.

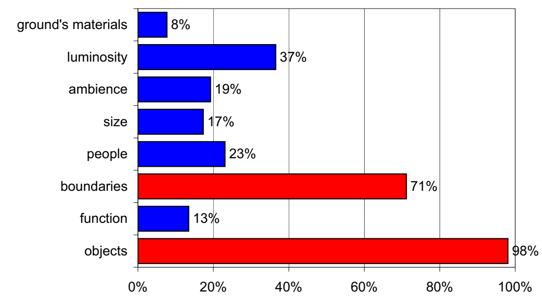

Fig. 20. Means of representation of an office. Objects = { desk, drawers, chair, books,...}, function = { place to work }, boundaries = { 4 walls, big window, door }, people = {several people sharing space, one person }, size = { not too large, 30 m^2 }, ambiance = { pleasant, active, sober }, luminosity = { natural light, artificial light, dimly lit, 'strip'/tube lighting}

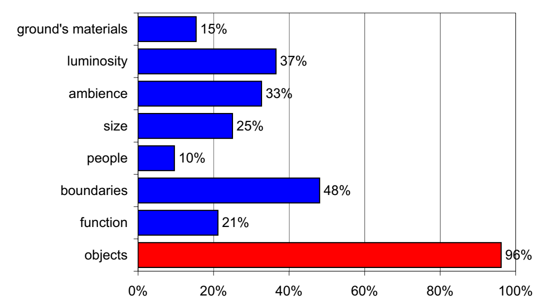

Fig. 21. Means of representation of a living room. Object = { sofa, armchair, coffee table, TV }, function = { place for rest, place to meet people, place to watch TV }, boundaries = { many windows, 2-3 doors leading to other rooms, high ceiling }, size = { big place, 40-50 m^2 }, ambiance = { calm, live, congenial, convivial }, luminosity = {natural light, very illuminated, big lamp for whole room }, ground materials = { carpet flooring }

2) Description: People were taken to different places and were asked to describe what they saw in as much detail as possible. The means of describing an office, a refreshment room and a laboratory-office are respectively shown in figures 23 24 and 25. In this case the objects and functionality of the place show significantly more importance than boundary elements.

3) Change of Place: The objective of this part of the study was to identify what leads to the formation of a place and how do humans sense that they are in a new place. People were taken from one place to another and queried as to when and why they believed that they were in a new place. The categorized results are depicted in figure 26. Clearly, boundary elements such as doors and walls and

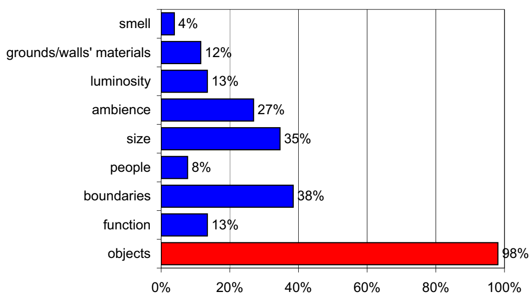

Fig. 22. Means of representation of a kitchen. Objects = { cooker, oven, fridge }, function = { place to eat, place to cook }, boundaries = { many windows, 2-3 doors leading to other rooms }, people = { family, kids }, size = { small, not very big, spacious }, ambiance = { sober, functional, clean }, luminosity = { bright }, ground materials = { tiled flooring }, smell = { food, good smell }

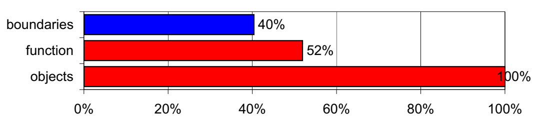

Fig. 23. Means of description of an office. Object = { desks, drawers, chairs, pens }, function = { place to work } and boundaries = { windows, closed space }

object arrangements constituted the most important criteria determining a change of place.

4) Analysis: The reason both representation as well as description details were sought from users was to maximize the data we have - both from a time-accumulated model (representation) of the place and an in-situ description. Objects were clearly the feature of choice when it comes to representing or describing places. Another significant element in this regard were boundary elements such as doors and walls. This seemed logical as the motivation for our approach is that objects provide the necessary semantics of the space while the boundary elements provide for the structure. However, boundary elements seemed relatively insignificant in the descriptions of places where the functionality was the principal component. Boundary elements such as doors and walls and object-arrangements turned out to be the most significant factors in determining a transition from one place to another. There were several other factors which were less significant but nevertheless worth consideration. Together, these could be understood as some sort of 'visibility' measure of a place.

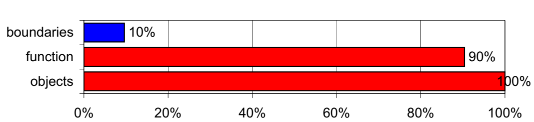

Fig. 24. Means of description of a refreshment room. Object = { sofa, armchair, table, shelves }, function = { place to relax, place for a coffee, place to read } and boundaries = { windows, door, walls }

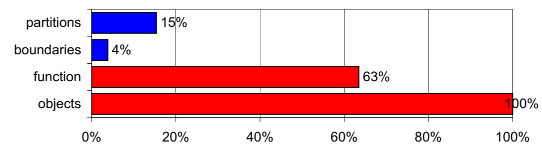

Fig. 25. Means of description of a laboratory-office. Objects = { workspaces(tables and chairs), wires, tools, oscilloscope, robots }, function = { place for theoretical and practical work }, partitions = { the shelves that separate the workshop like area from the office like area } and boundary elements refer to the typical boundary elements such as windows, door and walls

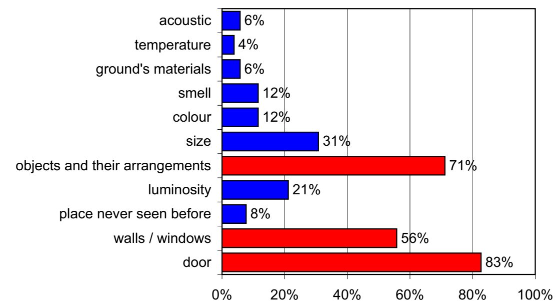

Fig. 26. Means of place formation / identifying a change of place. People cited a change in the objects and their spatial configuration, typical boundary elements such as doors and walls as a means of determining the occurrence of a new place. Other factors that were cited include a change in light intensity (luminosity), a sudden change in size / color / smell / ground materials/ level of sound and even temperature (places towards the interior of the building are significantly cooler than the areas near windows)

E. Hierarchical spatial representation

The objective of this part of the study was to somehow establish that a hierarchical representation may be a possible explanation to the way humans represent routes and space. People were asked to describe the route from the meeting point to the their current location (the same room for everyone). Their answers were categorized and are depicted in fig. 27.

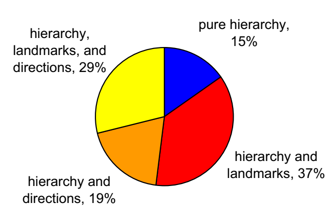

Fig. 27. Types of route encoding. A pure hierarchy represented a succession of path elements that simply jumped from one level of abstraction to another (for e.g. from building to floor to corridor to room), as mentioned before different people preferred to enrich their descriptions using landmarks, directions and even a combination of them.

1) Analysis: As observed from the graph above, every single subject gave some form of a reply that contained a hierarchical sequence of structural elements such as the floor - corridor - room sequence etc. However, people also made use of landmarks, directions and distance measures. The exact proportion of the combinations were also quantified and this seemed to suggest that a hierarchical sequence of structural elements with a combination of one / more landmarks was the most popular option.

IV. Discussions & Future work

The study brought out some interesting perspectives from the point of view of the overall approach. The most significant ones are listed below. Some aspects of the survey turned out to be well addressed while others could do with better treatment; there are still others which are too difficult to truly address and it is hard to find an appropriate way to glean or infer such information ordinarily.

- The word "cognitive", in the context of this approach, is more likely human-compatible and not necessarily human-like. Design decisions of the approach and results from the survey guarantee that the representation so formed is cognitive in that it is human compatible but are insufficient to estimate the similarity with the representation of the information in our brains. Future work will attempt drawing parallels and understanding the exact differences between the various schools of thought on the brain's cognitive map - as perceived by cognitive psychologists, neuroscientists and roboticists. Work would also be dedicated towards conducting more insightful user studies on the theme of this work.
- An object based representation is indeed useful for robots to develop a human compatible representation of space.
- Objects are grouped into groups or concepts - these are the semantic / functional abstractions in space. They are mostly formed by similarities in purpose, functionality and also by the relative spatial arrangements of objects.
- Places can be understood as spatial abstractions which are typically formed by bounding elements such as walls and doors.
- The survey brought out to a significant extent, the various properties, functionalities that may be relevant towards enhancing the representation being pursued.
- Typical groups (functional groupings of objects) that are formed by humans were also identified in the places where the users visited. This does give some ideas for other kinds of places too.
- Spatial abstractions contain semantic ones. This was indicated to a certain extent and subsequently taken as a design decision.
- A change of place was typically identified as a result of the occurrence of boundary elements such as doors or walls and also that of a significant change in the kinds of objects and relative spatial arrangements of objects.
- The structure of objects is critical to representing or describing them. Its material composition and type were also important. Scene descriptions were typically end-to-end or based on a central object.

The following issues warrant further research. Most have been attempted in this work. They produced results that were deemed insufficient (as discussed in earlier sections). Some are very hard to actually ask without biasing subjects. Some others were intermediate realizations of the study itself.

- Is space actually represented as a hierarchy? Are there spatial and semantic abstractions in our brains?
- Does the spatial abstraction contain the semantic one?
- The role of human activity. This issue is beyond the scope of the presented study. Both at the level of objects, how they are classified and at the level of functional spatial representation, this issue needs to be studied.
- In the context of object recognition, is the structure alone important? When and why does functionality come into play?

The representation proposed herewith, can enable a robot to develop a human-compatible representation of space and even a human-like conceptualization of space. It can equip robots with more than "just" navigational capabilities, make them much more spatially cognizant machines and yet ensure that they are still compatible and acceptable to us. This report sought a human perspective towards validating the approach and a feedback on how the representation could be enhanced. Both tasks have been successfully addressed. The study provides an empirical basis for certain facts that seem to be taken as obvious or concepts that are intuition inspired. Questions that are yet to be addressed or insufficiently addressed in this work were also identified for future work.

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