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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 33(33)

ISSN
1069-7977

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Publication Date
2011

Peer reviewed

Everyday Navigation in Real and Virtual Environments Informed by Semantic Knowledge

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Abstract

The effect of semantic knowledge on performing an everyday wayfinding task was investigated in real and virtual grocery stores. Participants had to search for 15 food items exhibiting varying degrees of congruency with background knowledge with respect to their placement in a mid-sized supermarket. Food categories and the congruency of categories with the placement of pertinent food items was assessed pre-experimentally using a card-sorting task with customers and store managers. Experiment 1 was conducted in a real supermarket (tracing participants by means of RFID techniques) and replicated in the same market as a virtual environment (Exp. 2), allowing insights into potential differences. Exp. 3 used a VR variation where all the pictures on the shelves of the VR supermarket were replaced with printed labels. Results regarding semantic knowledge yielded stable and fairly high effect sizes across experimental conditions, revealing that semantic congruency with shopping goods' placements made the search for food items much more efficient. The results show that even abstract background knowledge (semantic categories) may be involved in human navigation.

Keywords: Navigation, wayfinding, semantic knowledge, virtual reality, spatial cognition.

Presenting background knowledge as a decisive factor in human everyday cognition, sounds like nothing new in cognitive science. Not quite so in spatial cognition, specifically in wayfinding, and navigation in general. In contrast to the largely empty mazes so popular in experimental studies of human navigation, everyday navigation takes place in urban environments that are crowded rather than devoid of objects: streets are full of shops, offices, and restaurants, rooms are rarely empty but have furniture, or goods of any kind. An extreme case is the grocery store that typically has thousands of items on sale, quite the opposite to an empty room.

When shopping, customers must find their way around. when shopping for everyday goods like groceries, or hardware. The everyday foraging of humans has to be fast and successful. Therefore, people should be oriented in a supermarket (Underhill, 1999). Our study identifies what makes this kind of navigation efficient.

Human navigation has been studied extensively in the laboratory, and occasionally in the wild. In the seminal study of Thorndyke and Hayes-Roth (1982), navigation in a real building was shown to make use of the building's geometry, as well as of episodic memory (i.e., having been in this building before). Recently, following their lead, a number of studies have addressed navigation in indoor and urban environments (e.g., Hölscher, Büchner, Meilinger, & Strube, 2009; an overview of different wayfinding tasks and respective studies can be found in Wiener, Büchner, & Hölscher, 2009). The findings of these studies underline that the factors influencing human navigation enumerated by Wang and Spelke (2000; 2002), namely, path integration, view-dependent place recognition, and reorientation by geometric properties, appear to be modified by strategic behavior and background knowledge. In contrast to episodic knowledge (i.e., familiarity with the environment), this knowledge may be characterized as generalized experience with similar (esp. human-made) environments, like the usual placement of staircases, or hallways in public buildings. We suppose that with regard to supermarkets, it is semantic knowledge – knowing about the categories of food – that guides customers in their daily hunt for what is needed to feed the fridge and the oven, and ultimately, us and our families.

We will first report how the experimental items were selected on the basis of food-related semantic knowledge, and follows with a real-world experiment in a supermarket where we tested how helpful this knowledge was in a search task. We then present a replication experiment in a virtual supermarket setting, and follow with another replication that exchanges the visual appearance of goods with verbal labels, in order to test the possible influence of concrete visual information against abstract semantic information.

Knowledge of Food Categories

A group of six grocery store managers and another group of 32 naïve customers (19 female, 13 male; mean age 36.7 years) were tested individually. All participants were handed 98 small plastic cards naming typical grocery store goods and were asked to sort them into arbitrarily sized groups, then find suitable verbal labels for the categories they had constructed, and pair-wise ratings for the similarity between groups (Kalff & Strube, 2008).

The results were used to derive items for the search task in Exp. 1 to 3. Five items each were selected for three item groups, A to C:

Item group A: Items placed together (in the shelves of the supermarket) with others that received high similarity

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ratings (knowledge-congruent items: yoghurt drinks, canned corn, cake decoration granules, long grain rice, gravy powder),

Item group B: misplaced items, placed together with other items that received low similarity ratings with them (knowledge-incongruent items: *cereal bar, packaged marble cake, deli olive oil, vanilla yoghurt, pickled herring*),

Item group C: items on which customers (as well as shop managers) disagree with respect to their grouping and/or similarities to other items (*non-categorizable items: salt, fresh yeast, tomato puree, baby food, UHT milk*).

Experiment 1 (in the real supermarket)

Method

Participants. Thirty-eight participants (22 women and 16 men) aged 19 to 38 (M = 23.63, SD = 3.94) took part in the experiment. They were mainly cognitive science students from the University of Freiburg. They were recruited through advertisements on the campus and via an e-mail distributor. Participants were either awarded course credit or received a monetary compensation. The instruction deliberately did not mention any terms regarding supermarkets or (grocery) shopping, solely referring to a navigation task inside a building.

Procedure. The complete experimental procedure lasted approximately two hours. All participants were tested individually. Participants were welcomed at a playground in the vicinity of the supermarket. They were first handed a letter briefing them on the course of events and explaining the use of the equipment. Then they had to fill in a questionnaire probing for preferences in spatial orientation (the FRS-questionnaire, Münzer & Hölscher, accepted)[2]. The (underground) supermarket was then entered from the parking deck via the back entrance to prevent participants to gain an overview of the environment. Subsequently the main search task (see below) was initiated.

After completing the search for 15 items (trials), participants were led outside again to complete the following post-tests. Roughly half of the participants filled in a Euclidean distance estimation matrix consisting of 8 items. The other half was asked to execute 15 triple-comparisons (identifying the smallest Euclidean distance of three items constituting triangles). All participants subsequently had to produce a semi-free sketch-map of the supermarket environment. This was followed by a post-experimental evaluation of the shopping frequency for the 15 items and the frequency of visits to this particular store and stores of the same brand in general. Participants were also asked to give written responses regarding their strategies for finding the items. Finally, participants were handed a questionnaire on general shopping behavior and demographic data.

Experimental tasks. The experiment consisted of the main search task and several pre- and post-tests.

The search task was conducted in a medium sized (approximately 800m^2/ 8611 ft^2 of sales area) German supermarket housing some 15.000 product. Figure 1 shows the supermarket environment and the locations of the 15 items (see Table 1 for explanations).

The starting point (depicted with an asterisk) is at the first set of shelves, not at the entrance. This was mandatory as the experiment was run during normal store opening times and we did not want to obstruct the customer flow. Data collection was supported by technologically advanced apparatus. For obtaining participants' trajectories we relied on Radio Frequency Identification (RFID) (Joho, Plagemann, & Burgard, 2009). For this purpose 350 RFID Tags were distributed throughout the store. The tags (small antennae, in fact) were tracked through a custom-made shopping cart carrying two RFID-antennae along with a laser range scanner and a notebook computer. Participants were instructed to stay always close to the shopping cart, providing valid trajectory data. Additional behavioral measures and related positions were recorded using the real-time logging software *WayTracer* developed by Kuhnmünch and Strube (2006). *WayTracer* was installed on a notebook with a pen-enabled screen that was carried by an experimenter walking behind the participant.

Item token	Item name
X_1	Yoghurt drinks (A)
X_2	Cereal bars (B)
X_3	Tinned maize (A)
X_4	Salt (C)
X_5	Cake decoration granules (A)
X_6	Delicatessen olive oil (B)
X_7	UHT-milk (C)
X_8	Long grain rice (A)
X_9	Packaged marble cake (B)
X_{10}	Tomato puree (C)
X_{11}	Vanilla yoghurt (B)
X_{12}	Gravy powder (A)
X_{13}	Pickled herring (B)
X_{14}	Baby food (C)
X_{15}	Fresh yeast (C)

Table 1: Explanation of the abbreviations used in Figure 1 and group memberships of the experimental items in parentheses ('A' being congruent, 'B' being incongruent and 'C' exhibiting possible incongruence—or twofold equivocality).

Items were searched for one-by-one and the detected item always provided the starting point for the next trial. The order of the items can be found in Table 1.

[2] This questionnaire is a German version of two well-established measures used in spatial cognition research: the SBSOD [Santa Barbara Sense of Direction Scale] developed by Hegarty et al. (2002), and the QSR [Questionnaire on Spatial Representation] (Pazzaglia, & DeBeni, 2006).

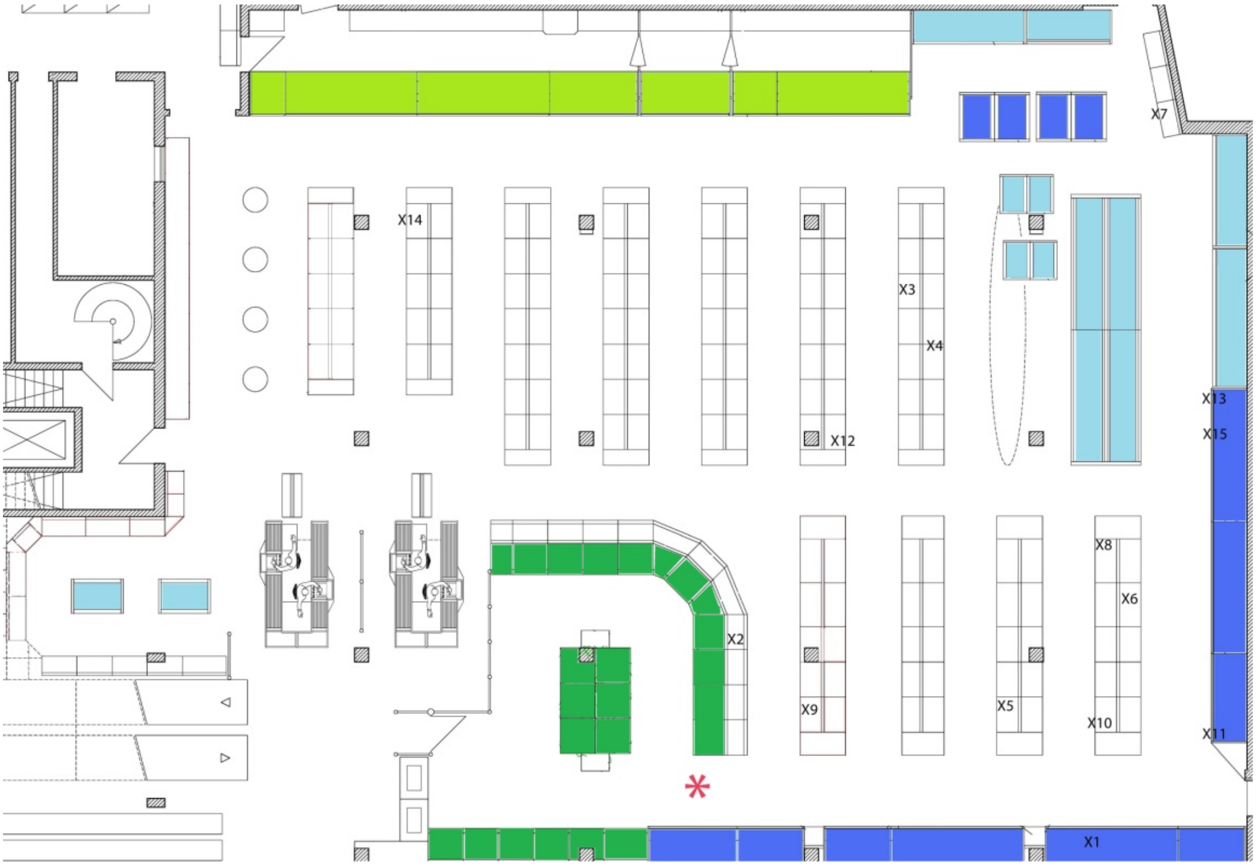

Figure 1: The supermarket environment. The entrance is located at the bottom left. The produce section is marked by dark green coloring. Dark gray is used for the produce section and for the shelves that house cooled products (mainly dairy goods). Light gray is used for deep-frozen food and sales counters for meat, cheese, and fish. All other shelves remain uncolored. The starting point for the experimental trials is marked by an asterisk.

An abort criterion was defined as follows: Participants were encouraged to search until they found the product. If they still hadn't found it after having explored the entire supermarket area (often overlooking the particular item repeatedly), the experimenter stopped the trial. Then they were led to the correct location for the next trial to begin. After all 15 items were processed, participants were led outside the building to complete the post-tests.

Materials: The 15 items shown in Table 1 were to be found, starting with x1, finishing with x15 (in the fixed-order condition; semi-randomized and completely randomized conditions were also done to corroborate the results).

Results and Discussion

Main search task. The following results for the main search task are those for the fixed-order condition..

After excluding 18 trials when items had not to be searched for, but merely headed to, 541 valid search time trials remained. Search times were adjusted with respect to the route distance that had to be travelled to reach the items in an optimal way (the shortest possible path), and the (average) amount of weekly visits to our test store (the only predictor using a backward multiple linear regression; r^2 = .137, $p > .001$). Outlier correction removed 18 data points that exceeded three times the interquartile range, leaving 523 trials for the analysis. The ANOVA (with participants as a random factor) shows a significant influence of background knowledge congruency on search time: $F(2, 78.165) = 69.847$, $p < .001$, partial-$\eta^2 = .641$. Games-Howell post-hoc comparisons reveal significant differences between all three conditions: all $p < .001$ with group 'A' outperforming the groups 'B' and 'C' and group 'C' ranging between the two others (see Figure 2). A planned Helmert contrast between group 'A' and groups 'B & C' likewise exhibits a significant difference for the adjusted search time ($p < .001$).

Two other important dependent measures are the travelled route distance for finding the items and the amount of stops during the search. Route distance will be reported as the percentage above optimal (PAO), i.e. the overshoot of the optimal path length expressed in percentage of that optimum:

$$PAO = \frac{Travelled\ Route - Optimal\ Route}{Optimal\ Route} \cdot 100.$$

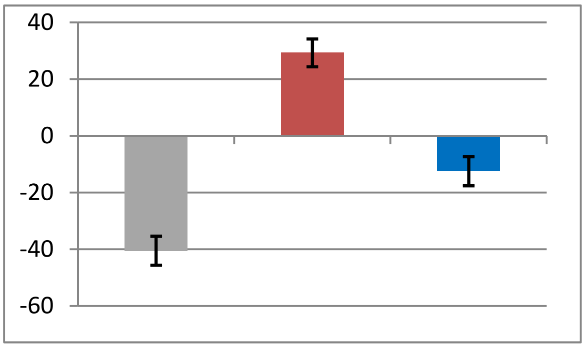

Figure 2: Search time corrected for optimal route distance and weekly visits to the particular supermarket-environment for the three groups (A, B & C, from left to right). Error bars = ± 1 SE.

The travelled route distance was obtained by processing the RFID data. The exact procedure of extracting spatial information from RFID signal strength is explained in Joho, Plagemann, and Burgard (2009). Conversion of the X,Y-coordinates into trajectories was achieved by applying a MatLab-script. The complete trajectory data was split into trials and output to the main data file. The outlier removal consisted of removing all trials excelling three times the interquartile range. This left us with 476 valid trials. These were also subjected to a random-factor ANOVA resulting in a main effect of congruency with background knowledge categories: $F(2, 80.4) = 66.603$, partial-$\eta^2 = .624$. The Helmert contrast comparing group 'A' with 'group B & C' is highly significant, $p < .001$, as are all Games-Howell post-tests (all $p < .001$). They also correlate highly with search time ($r = .761$ and $.746$) and among each other ($r = .869$). Search times, PAO values, and number of stops in a search trial all correlated higher with each other (PAO and Search Time, $r = .761$; PAO and Number of Stops, $r = .896$; Search Time and Number of Stops, $r = .746$; all $p>.001$).

These results clearly show the impact of semantic background knowledge about food categories in a real environment.

Experiment 2 (in the virtual supermarket)

The objective of Exp. 2 was to replicate our real-world findings in a virtual reality version of the supermarket (see Figure 3) in order to gain insight into the comparability of the two settings, since results from real, as compared to virtual environments, have sometimes been found to disagree with those in real-world environments (e.g., Farell et al., 2003; Richardson, Montello & Hegarty, 1999). The third experiment for example (which will be reported after this one) will strip the products of all non-semantic information.

Method

Participants. 28 student participants (15 women and 13 men) aged 20 to 26 ($M = 22.54$, $SD = 1.45$) took part in the experiment. None of them had knowledge of the initial real-world experiment.

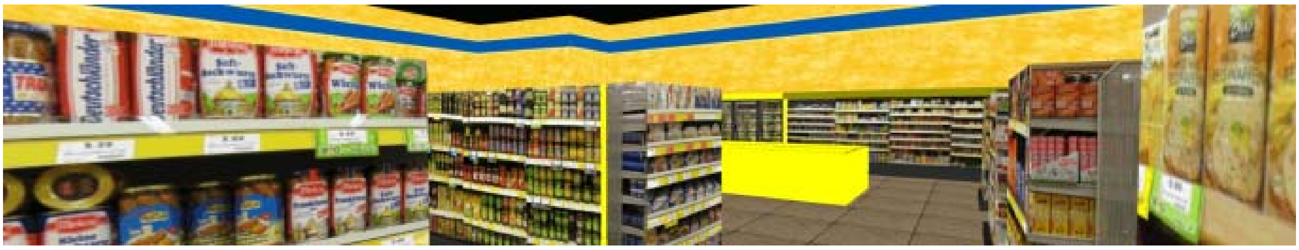

Figure 3: Screenshot of the supermarket in virtual reality (a faithful replication of the real supermarket).

Apparatus. All virtual reality (VR) experiments were conducted with a triple-screen setup. Each screen had a size of 28 inches and a resolution of 1360x786 pixels resulting in a total resolution of 4080x768 pixels with a color depth of 32bit and a refresh rate of 60Hz. For the navigation device we used a wireless joypad, which had two joysticks, one allowing to turn around and the other to go forward or backward. We didn't allow additional movement options like sidestepping or combinations thereof because this caused motion sickness during the pretesting phase in some cases. The maximum turning velocity used was 29 degrees per second and the maximum movement velocity was 1.8 meters per second. After finding an item one had to press a button on the joypad where (after the actual position was checked and if the person was located correctly) the next instruction was shown. For our virtual world model we used a ground plan which was consistent with the trajectory data of the real supermarket and contained information about the position and sizes of every shelf. Virtual shelves were modeled to scale an textured with images of food items that were actual photos taken in the real supermarket.

Procedure. The procedure paralleled the real-world experiment (Exp. 1) closely. The main search task was preceded by a brief training course in a different virtual environment.

Results and Discussion

Main search task. Data were treated in the same way as in Exp. 1; 367 valid trials remained for analysis. Backward linear regression on the residualized search time yielded two significant variables: shopping frequency of the experimental items (zero-order correlation $r = -.25$, $p < .001$), and self-assessed knowledge of the placement heuristics used in this supermarket chain ($r = -.123$, $p < .05$).

ANOVA with participants as a random-factor shows a significant influence of background knowledge congruency on search time: $F(2, 61.769) = 27.884$, $p < .001$, partial-$\eta^2 = .474$. Games-Howell post-hoc comparisons reveal significant differences between all three conditions: all $p < .001$ with group ‘A’ outperforming the groups ‘B’ and ‘C’ and group ‘C’ ranging between the two others (see Figure X3). A planned Helmert contrast between group ‘A’ and groups ‘B & C’ likewise exhibits a significant difference for the adjusted search time ($p < .001$).

As shown in Fig. 4, our results in VR parallel those of Exp. 1 almost exactly.

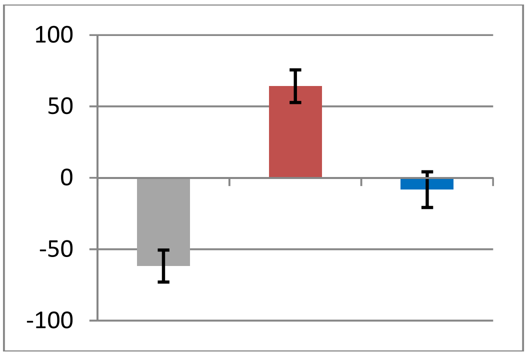

Figure 4: Search time corrected for optimal route distance, z-standardized item purchase frequency and knowledge of the store’s placement for the three groups (A, B & C, from left to right). Error bars = ± 1 SE.

Figure 5: A screenshot of the labeled supermarket.

Experiment 3 (VR, Verbal Labels Only)

Our results so far have shown that navigation in an everyday search task, either a real, or a virtual supermarket, was significantly influenced by knowledge of food categories. What remains to be clarified is the nature of this background knowledge: Is it plain semantic, conceptual knowledge, or does it need to be augmented by the looks of the items on sale? What if the complete environment would be stripped of coloring, type of packaging and other visual features that might create uniqueness? The ‘labeled’ supermarket aims at dissociating the influence of visual information and pure semantic background knowledge by replacing every item by a written label (see Fig. 5).

Method

With the exception of verbal labels instead of pictures on the virtual shelves, Exp. 3 replicated Exp. 2.

Participants. 28 students (15 women and 13 men) aged 19 to 30 ($M = 23.18$, $SD = 2.2$) took part in the experiment. In order to render the labels legible, not every single item received a written counterpart, but the grain size of the labels was well below that of the food categories used in our initial assessment of background knowledge.

Results and Discussion

After data conditioning (as in the former experiments), 410 valid trials were analyzed using a random-factor-ANOVA. Results show a significant difference regarding the three knowledge congruency groups: $F(2, 54.367) = 11.398$, $p < .001$, partial-$\eta^2 = .295$. Games-Howell post-hoc test prove significant differences between groups ‘A’ (congruence) and ‘B’ (incongruence) ($p < .001$), and groups ‘A’ and ‘C’ (twofold equivocality) ($p < .01$). The nature of these differences can be seen in figure Y_3. A planned Helmert-contrast between group ‘A’ versus groups ‘B & C’ is also highly significant ($p < .001$).

Again, the ANOVA results for Exp. 3 parallel those for Exp. 1 and Exp. 2, demonstrating that even when the supermarket environment has been ‘semanticized’, by stripping its items from their visual appearance, semantic background knowledge still turns out to be helpful. Fig. 7 shows the results not with the standardized search-time residuals, but with the PAO values.

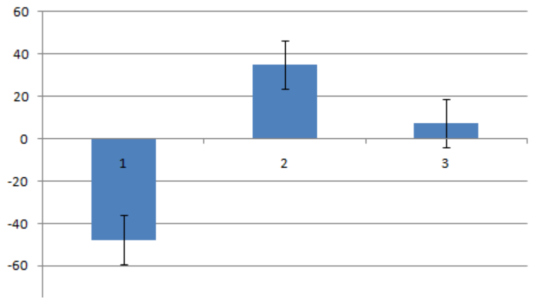

Figure 6: Search time corrected for optimal route distance, z-standardized item purchase frequency and knowledge of the store's placement for the three groups (A, B & C, from left to right). Error bars = ± 1 SE.

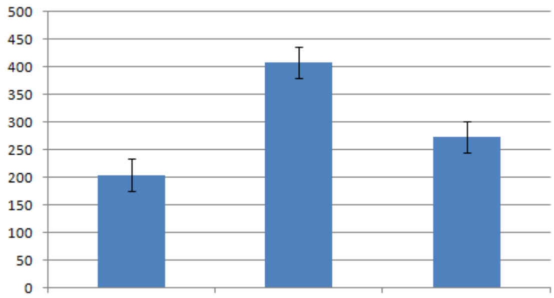

Figure 7: Travelled route distance expressed in PAO (percentage above optimal path length) for the three groups (A, B & C, from left to right). Error bars = ± 1 SE. The optimal, i.e., shortest path, corresponds to a value of 100.

General Discussion

The bottom line of our findings is that even abstract (semantic) background knowledge can be a decisive factor in human wayfinding. Other well-known factors (e.g., those cited by Wang & Spelke) may be mediated by background knowledge, and in certain environments, where this knowledge is applicable, guide navigation. The main point is that whenever the environment itself is structured according to semantic (or whatever) principles, as is often the case in urban, or other human-made environments, pertinent background knowledge will be useful to find one's way around, especially in search tasks. Large grocery shops like the 'real' supermarket where Exp. 1 was conducted, organize the layout of their products according to food categories (with some notable exceptions), so knowledge of food categories turns out to be helpful. Largely the same holds for conventional layouts of buildings, e.g. opera houses, where general knowledge about their spatial layout will be of help, or statistical knowledge about co-occurrences (e.g., in Germany, you will be well advised when looking for a medical doctor, to spot the next pharmacy, which is far easier to spot than a medical office).

We hope to have shown that for everyday navigation, at least, 'higher' cognitive processes like the utilization of semantic knowledge, may play an important part.

Acknowledgements

This work was funded by the Transregional Collaborative Research SFB/TR8 "Spatial Cognition" of the German Research Council (DFG). We thank the DFG, and also wish to thank Martin Senk, Dominik Joho, and our student research assistants B. Lammers, B. Schiffler, A. Nau, A. Leicht, F. Stein and S. Maciej. We especially thank Edeka Südwest GmbH, Offenburg, for cooperating in our research.

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